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Compact, In-Stack, Three Size Cut Particle Classifier

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COMPACT, IN-STACK, THREE SIZE CUT PARTICLE CLASSIFIER

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Program Report

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16. ABSTRACT

A compact, in-stack, three size cut particle classifier was designed, fabricated and tested. The classifier consists of a two-stage impactor and back-up filter designed to measure the particulate emissions from sources in three size ranges: >3μm, 1-3μm, <1μm.

Three sets of jet plates (two jet plates per set) are included. Each set is designed for a different flow rate; however, all particle size cutpoints produce data in the three size ranges of interest. A choice of flow rates is desirable to allow reasonable sampling times at particulate emission sources with both high and low mass loadings.

The classifier was calibrated in the laboratory with monodisperse aerosols from a vibrating orifice aerosol generator. In field tests at three power plants, particle size distribution by the classifier were compared to particle size distributions by Andersen and Brink samplers.

With this compact sampling system, measurements of the three size fractions are possible over a wide range of test conditions.

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COMPACT, IN-STACK, THREE SIZE CUT PARTICLE CLASSIFIER

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ABSTRACT

The goal of this research project was to design and construct a sampling system which could be used in programs to characterize particulate emissions from stationary pollution sources.

A particle size classifier (PSC) impactor was designed to accomplish this. It is a two-stage impactor made of anodized aluminum with stainless steel jet and collection plates. This PSC impactor is designed to measure the particle emissions in three size ranges: nonrespiratory (>3 μm), upper respiratory tract (>1 to 3 μm), and lower respiratory tract (<1 μm).

Three sets of jet plates (two jet plates per set) are included. Each set is designed for a different flow rate but with all particle size cutpoints to give data in the three size ranges of interest. A choice of flow rates is desirable to allow reasonable sampling times at particulate emission sources with both high and low mass loadings.

A complete sampling system was constructed for the PSC impactor including probe, pitot tube, temperature controller, magnehelic pressure guages, and flow rate metering orifices. The impactor and sampling probe are designed to fit into four inch sampling ports.

The PSC impactor has been calibrated in the laboratory with monodisperse aerosols from a vibrating orifice aerosol generator. Particle size distributions from PSC impactor data have been compared to Andersen and Brink impactor particle size distributions at three power plants.

With this compact sampling system, measurements of the three respiratory-related size fractions are possible over a wide range of test conditions.

This report was submitted in fulfillment of Contract No. 68-02-1736 by Southern Research Institute under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period June 21, 1974 to March 31, 1976 and work was completed on March 31, 1976.

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SECTION 1

INTRODUCTION

The particle size classifier (PSC) impactor is designed to measure the particle emissions from stationary pollution sources in three size ranges. These are the nonrespiratory (>3 μm), upper respiratory (≈1-3 μm), and lower respiratory tract ranges (<1 μm). With this compact sampling system, measurements of three size fractions within the flue gas over a wide range of test conditions are possible.

The impactor consists of a basic housing, a set of nozzles, a set of collection plates, and three sets of jet plates (two jet plates per set). The impactor is shown in Figures 1 through 4. It is an in-stack device that samples particulate emissions under stack or flue conditions.

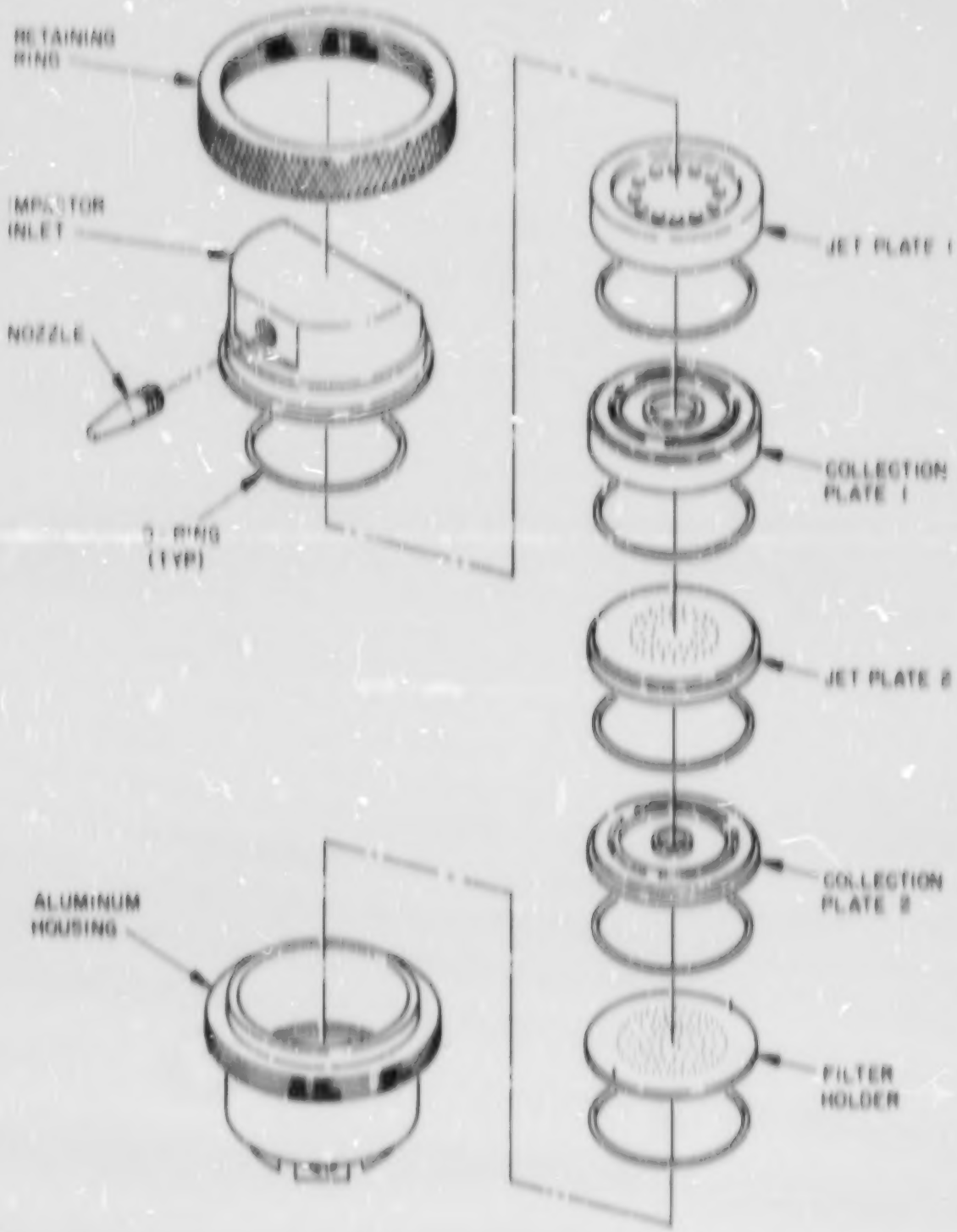


Figure 1. Particle size classifier (PSC) impactor.

Figure 2. Two-stage prototype impactor.
The impactor body is anodised aluminum.
The jet stages and collection stages are stainless steel.

Figure 3. Two-stage PSC impactor showing new outer shell with retaining ring and ¼" slots in base for pitot probe attachment.

Figure 4. Two-stage PSC impactor disassembled to show black anodized aluminum body and stainless steel collection plates and jet stages.

SECTION 2

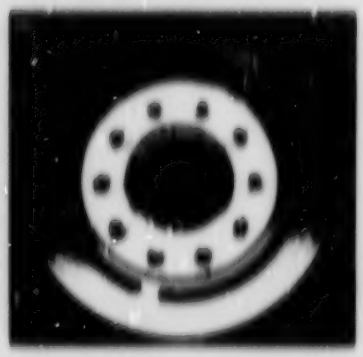
DESIGN OF THE PARTICLE SIZE CLASSIFIER IMPACTOR

The purpose of this contract was to devise and design a manual sampling train to measure the particle emissions from stationary sources in three size ranges. The design goal was to provide a compact, reliable system which could be used to obtain an accurate measurement of the three size ranges over a wide range of test conditions. Two general types of sampling systems were deemed capable of providing the desired measurements: a two-stage inertial impactor and a series cyclone system.

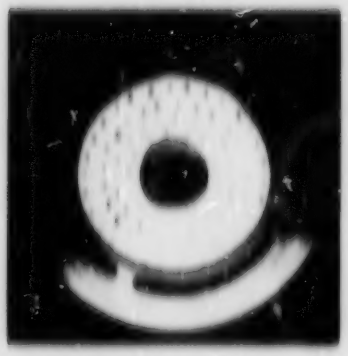
Tests with two cyclones assembled in series with a Gelman 47 mm filter holder showed the feasibility of a three-stage series cyclone. The collection efficiency curves for the cyclones were sufficiently sharp for good estimates of the amount of mass contained in each size range. The cyclone system, however, requires larger samples for accurate weighing, and at control device outlets with low mass concentrations the sampling time could become excessively long. Therefore, the two-stage inertial impactor was chosen.

Initial testing in the development of the two-stage impactor involved using various jet plates from either the Andersen Model III or University of Washington (Pilat) impactors. Jet stages were assembled into mock-up two-stage impactor configurations and tested with various monodisperse aerosols. Several combinations of flow rates and jet sizes were tested to study particle deposition, bounce, blow off, and reentrainment.

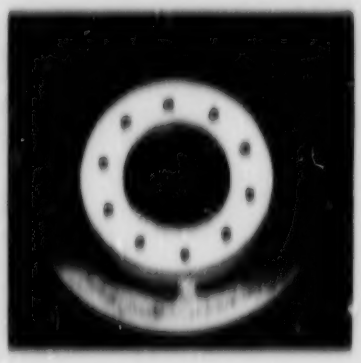
The basic result of all these tests was that the lower jet velocities resulted in more uniform particle deposition and greatly reduced particle reentrainment. Figure 5 shows data and illustrates this point. Jet stages from the particle size classifier (PSC) impactor were used. Figures 5A and 5C show impactor configurations where the D_{50} for each stage was 1.8 μm. In Figure 5A the jet velocity was 11.4 m/sec while in the case shown in Figure 5C the jet velocity was 4.2 m/sec. These jet stages were used to collect 2.8 μm diameter ammonium fluorescein particles. In the results illustrated in Figure 5A, 73% of the particles were collected, although ideally 100% would have been collected. In the results shown in Figure 5C, 92% of the particles were collected. In Figure 5A the deposited patterns of particulate matter



a. V_j = 11.4 m/sec
78% COLLECTION



b. V_j = 45.1 m/sec
78% COLLECTION
32% WALL LOSSES
IN a AND b



c. V_j = 4.2 m/sec
93% COLLECTION

d. V_j = 9.6 m/sec
94% COLLECTION
4% WALL LOSSES
IN c AND d

Figure 5. Particulate Deposition Patterns for Different Flow Rates, In all cases the particles were 2.8 μm diameter ammonium fluorescein spheres. a. D_{50}=1.8 μm, b. D_{50}=0.83 μm, c. D_{50}=1.8 μm, d. D_{50}=0.38 μm.

are not sharply defined but are blurred and smeared on the substrate while those in Figure 5C are nice, circular, compact deposits.

Figures 5B and 5D show stages that were downstream of those shown in Figures 5A and 5C. In the sample shown in Figure 5B, the D_{50} for that stage was 0.38 μm. For the configuration shown in Figure 5D, the D_{50} was 0.83 μm. Thus, collection of 100% of the particles should be expected. The jet velocity in Figure 5B was 45.1 m/sec and only 79% of the particles were caught. The jet velocity in Figure 5D was 9.5 m/sec and 94% of the particulate matter was caught. At the higher jet velocities, scouring and reentrainment were found to be significant.

Tests such as those described above indicate that a jet velocity of about 10 m/sec is the maximum which will give useful results for stage D_{50}'s of 1 micron and longer. In order to have D_{50}'s of 0.5 micron or less, a 10 m/sec limit is impractical, although as low a velocity as possible should be used. A lower velocity results in lower particle momentum, and lower particle momentum minimizes particle bounce and reentrainment. Wall losses are also reduced significantly when the lower jet velocities are used.

Careful attention was given to selection of size and number of jets for the PSC impactor to insure that jet velocities were under 10 m/sec or as low as practical.

A total of six jet stages were designed and constructed in an effort to make the impactor as versatile as possible. (See Table 1 for jet stage data.) Combinations of jet stages are available to permit sampling at flow rates from about 19 cm^3/sec for high grain loading situations to 94 cm^3/sec for low grain load situations while maintaining jet velocities below 10 m/sec.

DESCRIPTION OF CALIBRATION PROCEDURE

Laboratory evaluation of the PSC two-stage impactor involved the use of a Vibrating Orifice Aerosol Generator (VOAG) as a source of monodisperse aerosols. The VOAG used in this study was designed and built at Southern Research Institute, although similar devices have been reported by several authors previously[7,8,9] and a commercial version is available.* Figure 6 is a schematic diagram which illustrates the operating principle of the VOAG. A solution of known concentration [in our case, a solution of fluorescein ($C_{20}H_{12}O_5$) in 0.1N NH_4OH] is forced through a small orifice 5, 10, 15, or 20 μm in diameter. The orifice is attached to a

*Thermo-Systems, Inc., 2500 Cleveland Ave., N., St. Paul, MN 55113.

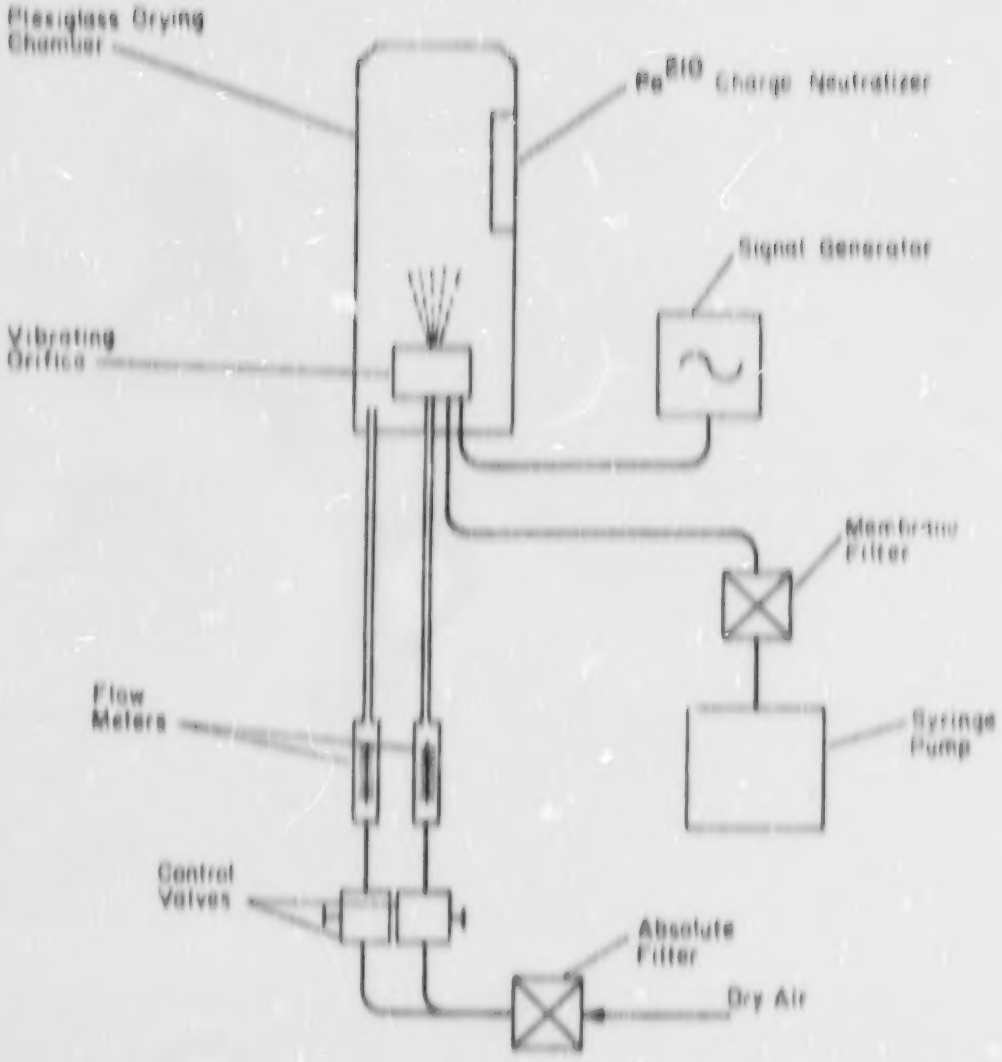


Figure 6. Schematic representation of the vibrating orifice aerosol generator

piezoelectric ceramic which, under electrical stimulation, will vibrate at a known frequency. This vibration imposes periodic perturbations on the liquid and causes it to break up into uniformly-sized droplets. The droplet size can be readily calculated from the liquid flow rate and the perturbation frequency. The solvent evaporates from the droplets leaving the non-volatile solute as a spherical residue. The final dry particle size can be calculated from the droplet size through use of the known concentration of the liquid solution.

The dry particle diameter, dp, is calculated from the expression

$$dp = \left(\frac{QC}{\pi CF}\right)^{1/3}$$

where C is the solution concentration or volume of solute/volume of solution,

Q is the solution flow rate (cm^3/min), and

F is the perturbation frequency (hz).

By using smaller orifices, one can obtain higher operating frequencies. This yields higher particle number concentrations and allows a shorter sampling time to collect the same mass per stage. The sampling time must be sufficiently long in each test to allow accurate determination of the stage collection efficiencies and wall losses. The 20 μm orifice was consistently easier to use in particle generation, primarily because of fewer clogging problems.

Prior to particle generation the orifices were washed in detergent with ultrasonic agitation and then rinsed several times in distilled water, also with ultrasonic agitation. After the filter and liquid handling system was flushed several times with the aerosol solution to be used, an orifice was placed, still wet with distilled water, into the crystal holder and the syringe pump turned on. A jet of air was played over the orifice to keep the surface clean until enough pressure was built up behind the orifice to form a jet.

After a stream of particles was generated, a determination of monodisperaity had to be made. Two methods were used to accomplish this. By using a small, well-defined air jet to deflect the stream of particles, it was possible to tell when the aerosol was mono- or polydisperse. Depending on the droplet size, the stream was deflected by the air at different angles. If the aerosol was polydisperse, several streams could be seen at one time. By adjusting the oscillation frequency of the crystal, the

system could be fine tuned to give only a single deflected particle stream, thus indicating monodispersity. Polonium-210 alpha sources were placed near the air stream as charge neutralizers to reduce the loss of particles due to electrostatic forces. A three-foot-high plexiglass cylinder was placed on the generator and dispersion and dilution air turned on to disperse, dilute and loft the particles into a plenum with several sampling ports. Because amonium fluorescein is nonhygroscopic and has physical properties similar to fly ash, it was used as the test aerosol, although in principle, any material that will dissolve readily in an evaporable solvent could be used. On several occasions, the aerosol tended to drift from monodispersity, and in order to protect against this occurrence, periodic filter samples were taken and checked by optical microscopy. This also provided a good check on the sphericity of the aerosol because the final particles were investigated instead of the primary liquid droplets. Optical microscopy thus served as a check on proper drying, satellites, correct size, and multiplets. Figure 7 shows one of the test aerosols generated. In general, about 8% or less by mass of the particles were of twice the volume (1.26 x diameter) of the primary particles.

After it was determined that particles of the correct size were being generated, samples were taken from the plenum with the two-stage impactor containing the appropriate jet stages. Noniso-kinetic sampling was performed; however, a series of tests indicated that this did not affect the collection efficiency of the impactor stages as compared to isokinetic sampling results. The nozzle losses were probably influenced by anisokinetic sampling.

At the conclusion of each test, the impactor was carefully disassembled and all internal surfaces cleaned with a solution of 0.1N NH_4OH. Each plate and surface was washed with a known amount of the solution to dissolve and rinse off the ammonium fluorescein particles.

The quantity of material collected on each surface was determined by absorption spectroscopy. A Bausch and Lomb Spectronic 88 Spectrophotometer, calibrated with solutions of known concentration of ammonium fluorescein, was used to measure the concentration of ammonium fluorescein in each wash. From a knowledge of the amount of wash solution, the dilution factor, if any, and the absolute concentration, the mass of particles on each surface could be calculated. With the mass on each plate and surface known, the wall losses and stage collection efficiencies could be calculated.

Several particle sizes were used to measure the stage collection efficiency curves. These were 15, 10, 7.0, 5.0, 3.8, 1.0, 2.0, 1.0, 0.7, and 0.5 micrometers diameter.

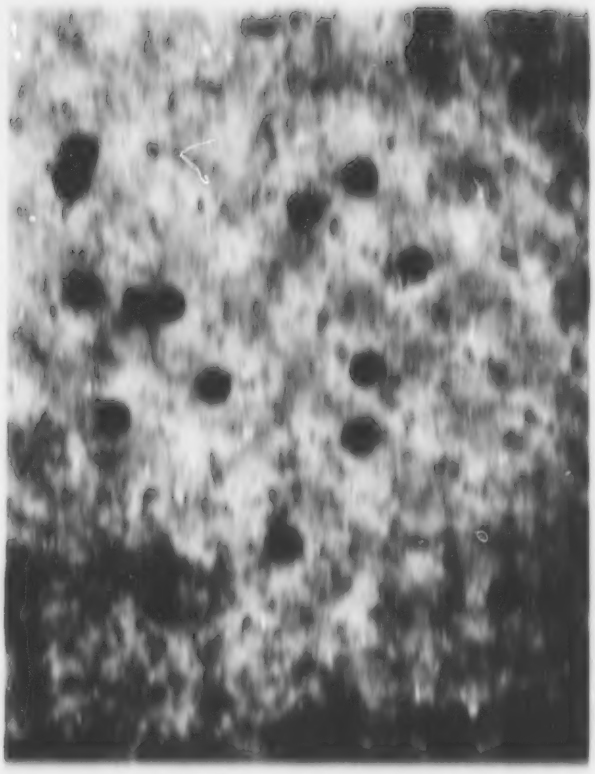


Figure 7. Ammonium fluorescein aerosol particles generated using the vibrating orifice aerosol generator. The particle diameters are 5.4 μm.

Wall Losses Versus Particle Size

Each surface of the impactor was washed individually after each test to obtain data on losses occurring in nozzles, inlet cones, jet plates, etc. Such losses can be attributed to particle settling, diffusion, electrostatic forces, bounce, and re-entrainment. In the majority of the tests the greatest losses occurred in the nozzles and inlet cones. These losses tend to decrease to a minimum at a diameter of about 1 microns and then remain low for smaller particles. The percentage total wall losses for the three jet plate sets are shown in Figure 8.

It should be pointed out that the majority of these particles are not irrevocably lost, but would be brushed onto the appropriate collection surfaces, or retrieved by washing.

PSC Impactor Description

The PSC impactor is a two-stage sampler with a backup filter, designed to fit through four-inch ports. The three sets of jet stages are all the round jet type and made of stainless steel. The first stage of each set has ten jets, and the second stage has either fifty or ninety jets. Table 1 contains the specifications for each set of jet stages. Each set of jet stages has a different designed flow rate as noted in the table. Each set of jet stages also has different nominal cutpoints to give the operator some latitude in selecting the cutpoints he wishes. Further cutpoint selections can be obtained by changing the flow rates over a limited range. The use of different flow rates for the stage sets also enables the operator to sample sources of high or low mass loading and still maintain reasonable sampling times. Jet velocities at these flow rates are all less than 10 m/sec.

The collection plates are made of stainless steel and are designed to accept doughnut-shaped collection substrates. The first collection plate has a larger center hole and a larger thickness than the second plate. The larger hole reduces the collection area; however, a large area is not needed for the single row of jets in the first jet stage. This larger hole is designed to allow smoother gas flow from the collection plate to the second jet stage with less loss of material. The greater thickness is necessary for the correct jet-to-collection-plate distance.

The final filter for the impactor is located just beneath the second collection stage. A standard 47 mm filter is used.

The impactor housing is made of anodized aluminum. Aluminum was chosen for its good heat transfer characteristics, which enables quick in-stack heating of the impactor to prevent conden-

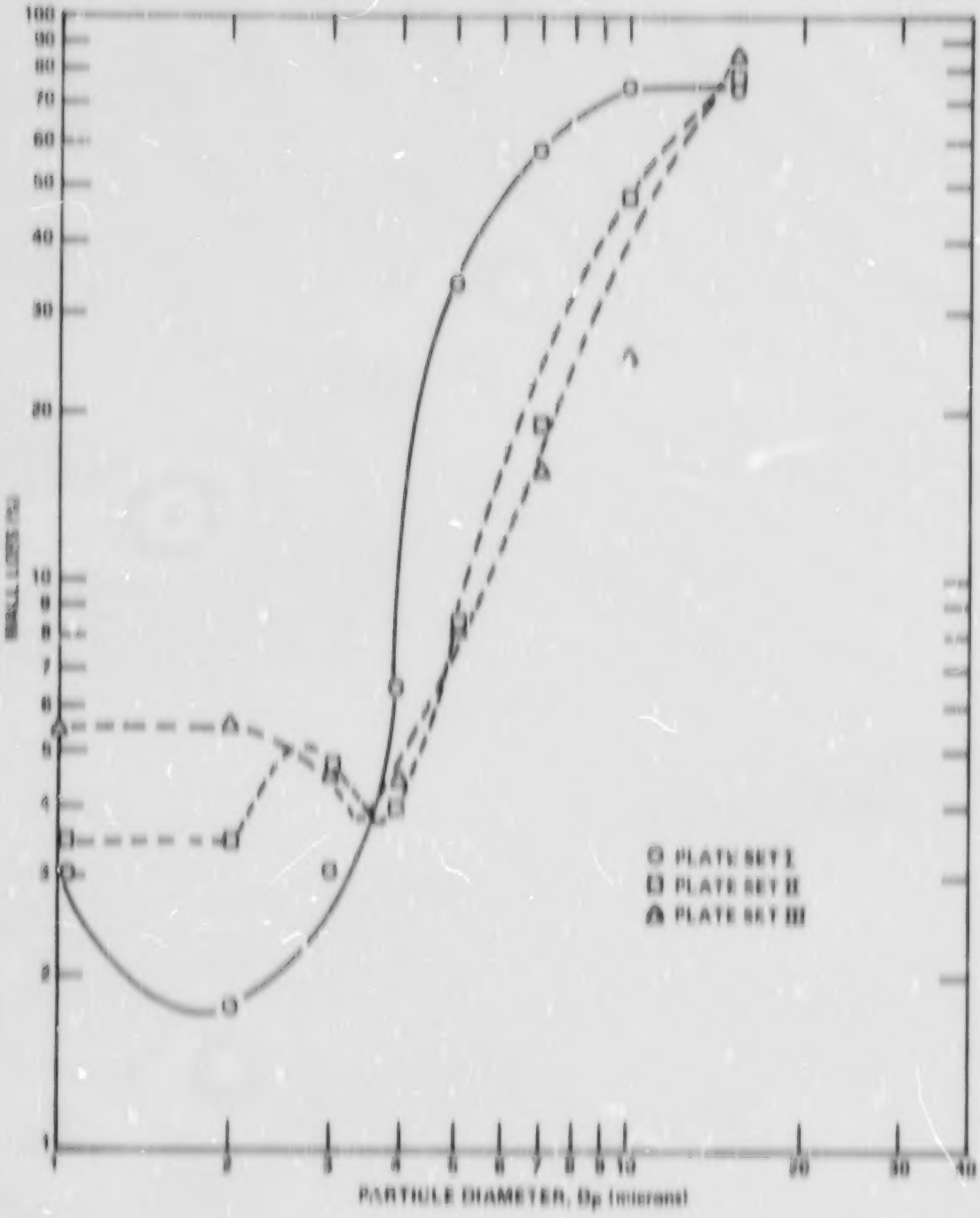


Figure 8. Wall losses versus particle size for the PSC impactor.

TABLE 1. JET STAGE DATA FOR THE PSC IMPACTOR

At designed flow rate, 22°C, and 749 mm Hg
for unit density spheres

Jet set	Stage	Designed flow rate	No. of jets	Dia. of jets, cm	Jet-to-plate spacing, cm	D_{50}, microns	Jet velocity, cm/sec	$\sqrt{D_{50}}$,
I	1	94 cm^3/sec (0.20 cfm)	10	0.325	0.56	6.40	114	0.195
	2		50	0.065	0.37	1.63	569	0.280
II	1	47.2 cm^3/sec (0.10 cfm)	10	0.167	0.56	4.80	215	0.310
	2		90	0.028	0.37	0.99	852	0.370
III	1	18.9 cm^3/sec (0.04 cfm)	10	0.088	0.56	3.00	311	0.295
	2		50	0.026	0.37	1.22	712	0.360

sation in the impactor. The anodized finish gives good corrosion resistance and makes the clean-up of the housing easier. The construction of the housing is such that the nozzle, which is threaded to fit the impactor inlet, can be aimed in any direction the operator wishes. Thus, for a horizontal port with either left-to-right or right-to-left gas flow, it is possible to have the nozzle pointed upstream and still have the impactor in a vertical position.

Ten stainless steel nozzles are included with the impactor for isokinetic sampling. These nozzles allow isokinetic sampling at flow rates from 19 cm^3/sec (0.04 cfm) to 94 cm^3/sec (0.20 cfm) in ducts with gas velocities of about 3 to 20 meters per second (10 to 70 feet per second). The nozzles' diameters are 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, and 6.0 mm. They are designed to allow the impactor to be inserted into four-inch ports.

Impactor Assembly and Preparation for Sampling

The collection substrates are specially shaped discs of glass fiber filter material. Other materials can be used to make substrates, although at present the glass fiber material seems to be the best for collecting dry particulate matter. In situations where the particulate matter is of a wet nature, aluminum or stainless steel foil substrates can be used. Grease can also be used with the metal substrates to aid particle retention. Teflon was found to be unsuitable for collecting dry laboratory particles, but worked well enough in field tests. A special punch for cutting the glass fiber substrates is included with this sampling system. Since both collection substrates have the same external dimension, a single punch works for both, and two interchangeable inner punches fit into the outer one for cutting the different center holes.

The substrates are prepared for field use by baking at 200 to 300°C for two to four hours to remove volatile matter and then desiccating for approximately 24 hours before weighing. A balance with a sensitivity of 0.01 milligrams is required to weigh the substrates since the amount of particulate matter to be collected could be less than a milligram. The substrates are placed in the collection plates after they have been desiccated and weighed.

The impactor is assembled with the collection substrates in place and a 47 mm backup filter on the filter holder plate as illustrated in Figure 1. Two types of o-rings (Parker No. 2-030) have been furnished with the impactor: Teflon and silicone. The silicone o-rings have an upper temperature limit of 232°C (450°F) and the Teflon o-rings are rated slightly higher. The silicone o-rings probably provide the best seal but they tend to

stick to the 47 mm backup filter more than the Teflon. A combination of the two types can be used.

Before the impactor is assembled, the housing, collection plates, and especially the jet stages should be thoroughly cleaned, preferably ultrasonically in a detergent solution. The jets must be clear and free of any obstructions.

The impactor is assembled from "the bottom up", as follows:

1. Place the impactor base on a flat surface.

2. Insert a silicone (or Teflon) o-ring in the base's o-ring groove.

3. Place the filter support on the base.

4. Center a pre-weighed 47 mm backup filter on the filter support between the guide pins.

5. Insert an o-ring in the groove on the bottom of the second collection stage and place this on the filter and filter support making sure that the guide pins on the filter support are inserted into their corresponding holes.

6. Insert a pre-weighed collection substrate into the second collection stage.

7. Place the selected second jet stage (with o-ring inserted in its groove) on the second collection stage.

8. Place the first collection stage (with o-ring inserted) on the second jet stage.

9. Insert a pre-weighed collection substrate into the first collection stage.

10. Place the selected first jet stage (with o-ring inserted) on the first collection stage.

11. Place the outer shell around the assembly and screw it to the base.

12. Attach the inlet cone with the retaining ring to the outer shell making sure that the intake is pointed in the proper direction.

13. Install the nozzle.

SAMPLING CONFIGURATION

The basic sampling train arrangement is shown in Figure 9. The stack gas passes in sequence through the impactor and probe, a cooling coil-condenser, an ice bath, a desiccant, an orifice flowmeter, and the vacuum pump. The condenser and drying column are used to insure proper measurement of the flow rate and gas volume and to protect the vacuum pump from damage. An insulated ice box for immersing the cooling coil-condenser is furnished. Two drying columns are mounted in the top of the insulated box.

In order to measure the flow rate, a calibrated orifice is used. Three calibrated orifices have been furnished with the system, one orifice for each of the designed flow rates. Procedures for the calculation of flow rates using orifice pressure drops are outlined below with all necessary equations given. The total pressure drop across the impactor and system components is needed for the flow rate calculation and is measured at a point just upstream of the orifice. Magnehelic gauges with various ranges are furnished in the impactor sampling case for measurement of these pressure drops. The impactor sampling case is shown in Figures 10, 11, and 12.

A gas meter can be used in place of, or in addition to, the orifice to measure the flow rate. Gas meter flow rate calculation procedures are given below also.

A vacuum pump is enclosed in the sampling case with a hose fitting for easy connection.

Sampling with the PSC Impactor

Isokinetic Sampling and Sampling time--

Included with the impactor is a reversed-type (S-type) pitot tube which attaches to the bottom of the impactor housing. The pitot should be attached to the housing so that its tips point parallel to the gas stream. Sampling and pitot readings should be done at a point in the duct where the velocity profile is uniform, preferably several duct diameters upstream and downstream of any obstructions or bends.

To determine a gas velocity from the pitot tube pressure reading, the following standard equation[3] can be used:

$$\text{Gas Velocity} = C(1096.2)\sqrt{\frac{P}{\rho}}$$

where C = Coefficient for S-type pitot = 0.86

P = Velocity pressure in inches of water

ρ = Gas density in lb/cu ft

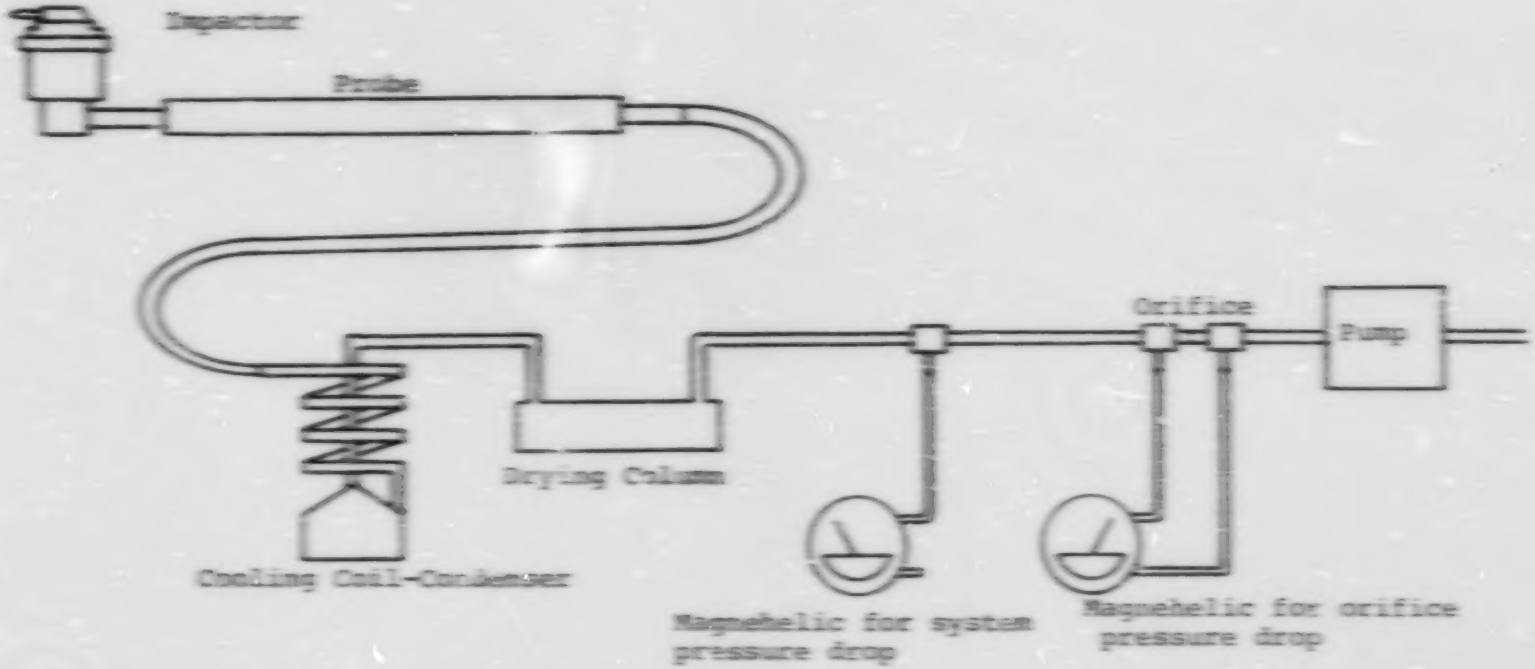


Figure 9. Typical sampling setup for PSC Impactor.

Figure 18. Two-stage impactor sampling case

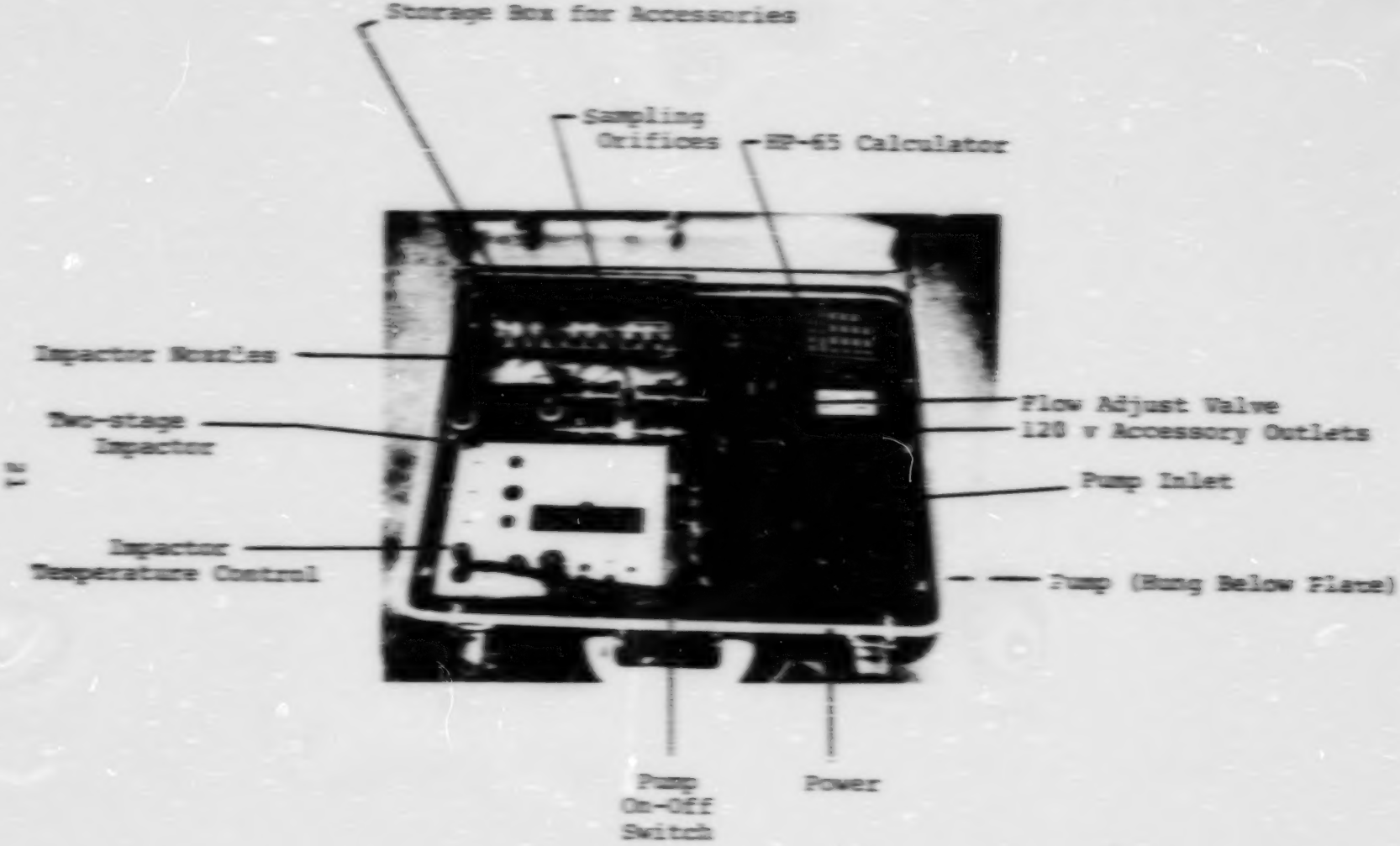


Figure 11. Two-stage impactor sampling case showing major operational components

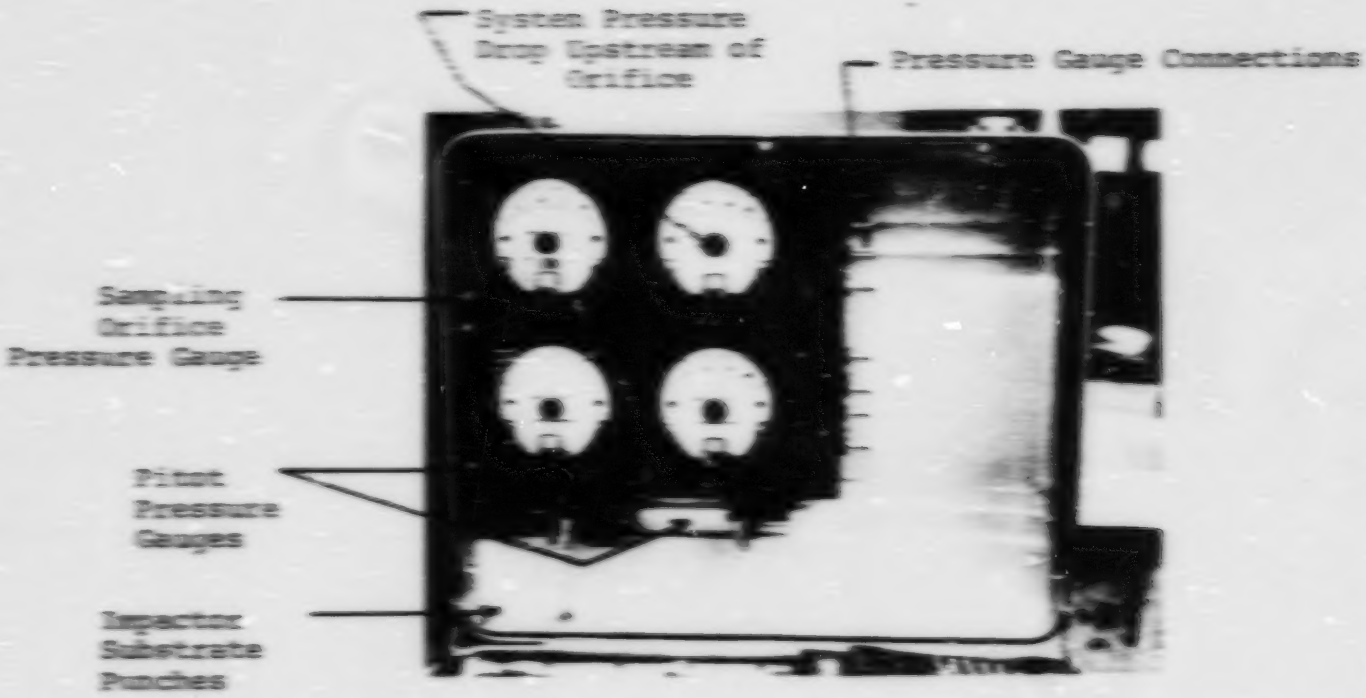


Figure 12. Top of sampling case containing pressure gauges and substrate punches.

Figure 13 is a chart for selecting the correct nozzle for isokinetic sampling at a particular flow rate. Isokinetic sampling is a must to obtain a representative sample and care should be taken to insure that it is accomplished.

The length of the sampling time is dictated by mass loading and particle size distribution. An estimate for initial tests can be made from Figure 14. This figure is used to obtain an estimate of the time required to collect a total of 25 milligrams at any of several flow rates which might be used. Tests subsequent to the first should have sampling times adjusted such that all stage loadings are kept below 10 milligrams.

Flow Rate Selection--

In high mass loading situations such as the inlet to control devices, a low flow rate is preferable because it will permit a reasonable long sampling time and process averaging. At the outlet of the control devices, the mass loading may be moderate to very low, and this situation will require the use of a high flow rate to avoid excessively long sampling times. The two-stage impactor with its three jet stage sets has the capability to handle both of these situations. For the high mass loading condition, one would choose the set with the designed flow rate of 18.9 cm^3/sec (0.04 cfm); and for the lower loadings, either the 47.2 cm^3/sec (0.10 cfm) or the 94.4 cm^3/sec (0.20 cfm) sets would work well.

After the mass loading, sampling time, nozzle, and jet stage set have been determined, the impactor can be assembled as described above, and then attached to the probe.

Before sampling can begin, the orifice pressure drop must be determined so that the flow rate can properly be set. The following equation gives the pressure drop across the orifice as read on the appropriate Magnehelic gauge:

$$\Delta P = \Delta P_a \left(\frac{Q_1}{Q_a}\right)^2 \left(1 - F_{H_2O}\right)^2 \frac{P_s^2}{P_a P_a} \frac{T_a T_s}{T_s} \frac{MM}{MA}$$

where

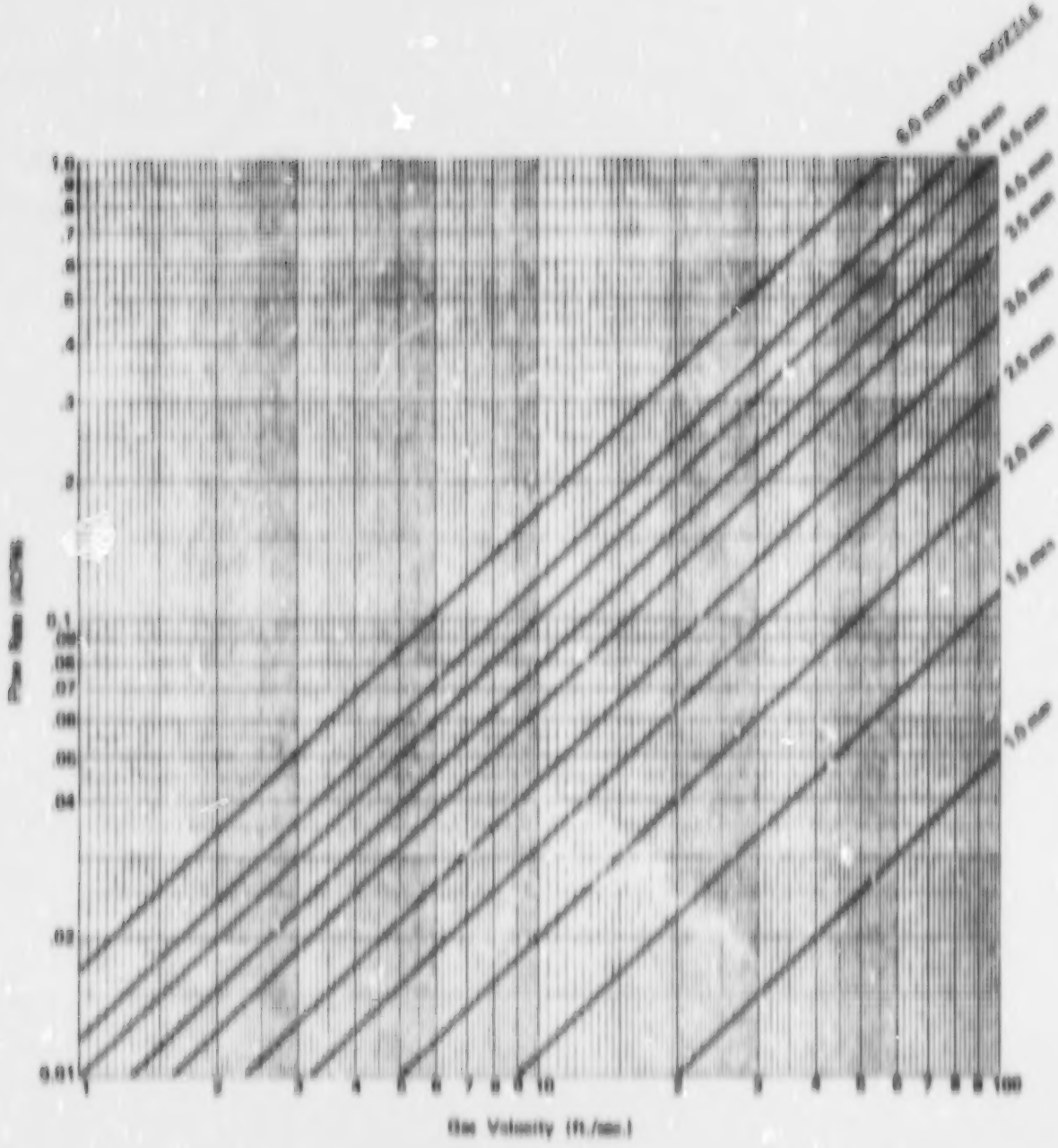


Figure 13. Nomograph for selecting nozzles for isokinetic sampling.

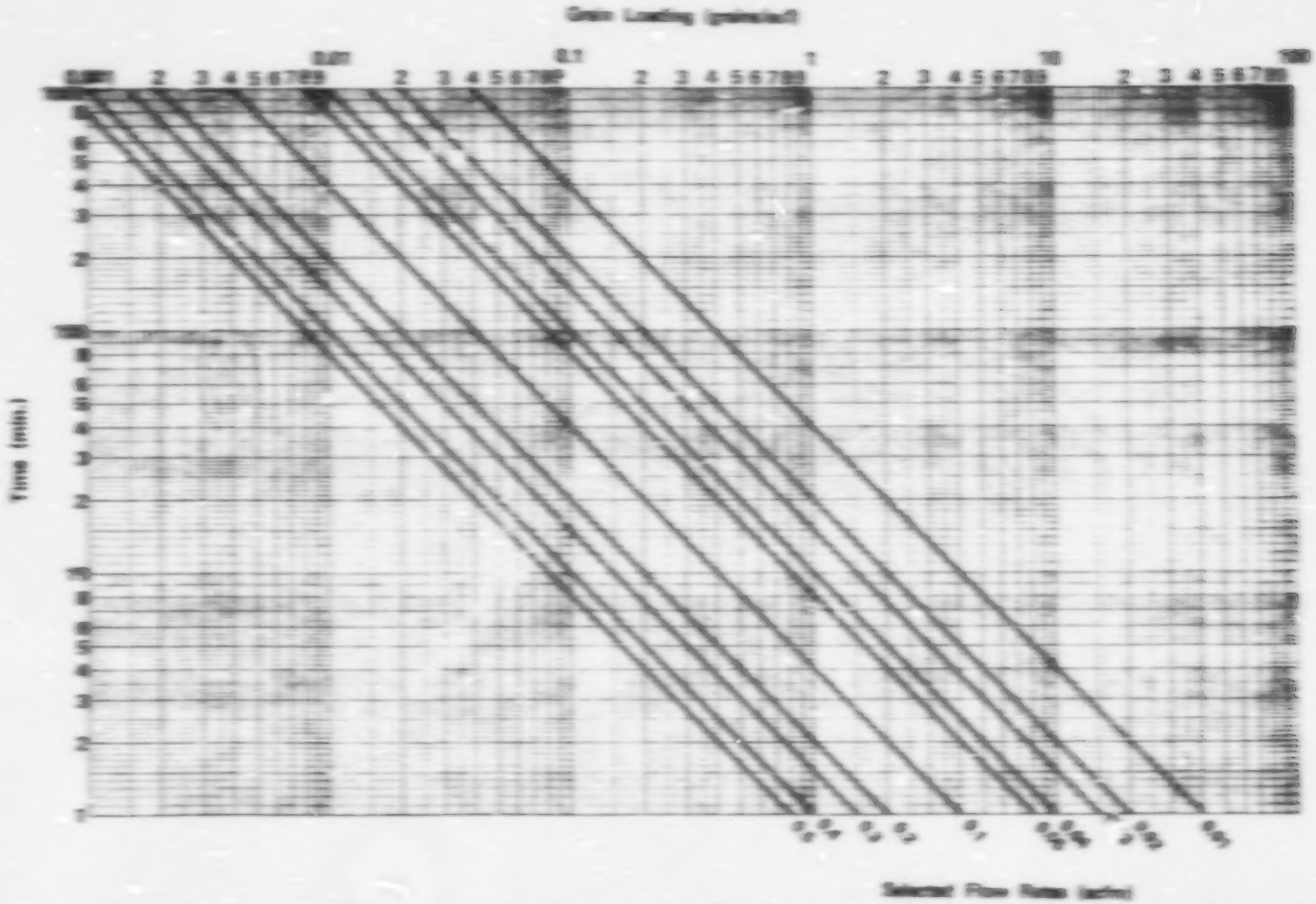


Figure 14. Sampling time determination for total mass collection of 25 milligrams.

MM	= Mean molecular weight of flue gas	
MA	= Mean molecular weight of air	
ΔP	= Calibrated orifice pressure drop (from Figure 15)	$"H_2O$
ΔP_o	= Pressure drop at which orifice calibrated	$"H_2O$
Q_I	= Impactor flow rate chosen for isokinetic sampling	ACFM
Q_c	= Calibration flow rate for orifice	ACFM
r_{H_2O}	= Volume fraction of water in the flue gas	
P_s	= Ambient stack pressure $P_s = P_A + \Delta P_s$	"Hg
P_o	= Pressure upstream of orifice referred to ambient	"Hg
P_c	= Ambient pressure when orifice calibrated	"Hg
T_o	= Temperature of the orifice	^oR
T_s	= Stack temperature	^oR

This equation has been incorporated into a program for the Hewlett-Packard HP-65 calculator. The program sheet included in this report details the use of the program to compute the pressure drop.

Notice that some of the input data are used with engineering units. This is for convenience in using the gauges and meters. The end results from all calculations, however, are in metric units.

A dry gas test meter can also be used to monitor impactor flow rate, either alone or in conjunction with a calibrated orifice. The following equation is applicable:

$$Q_m = Q_s \frac{T_A}{T_s} \frac{P_s}{P_A} (1 - F_{H_2O})$$

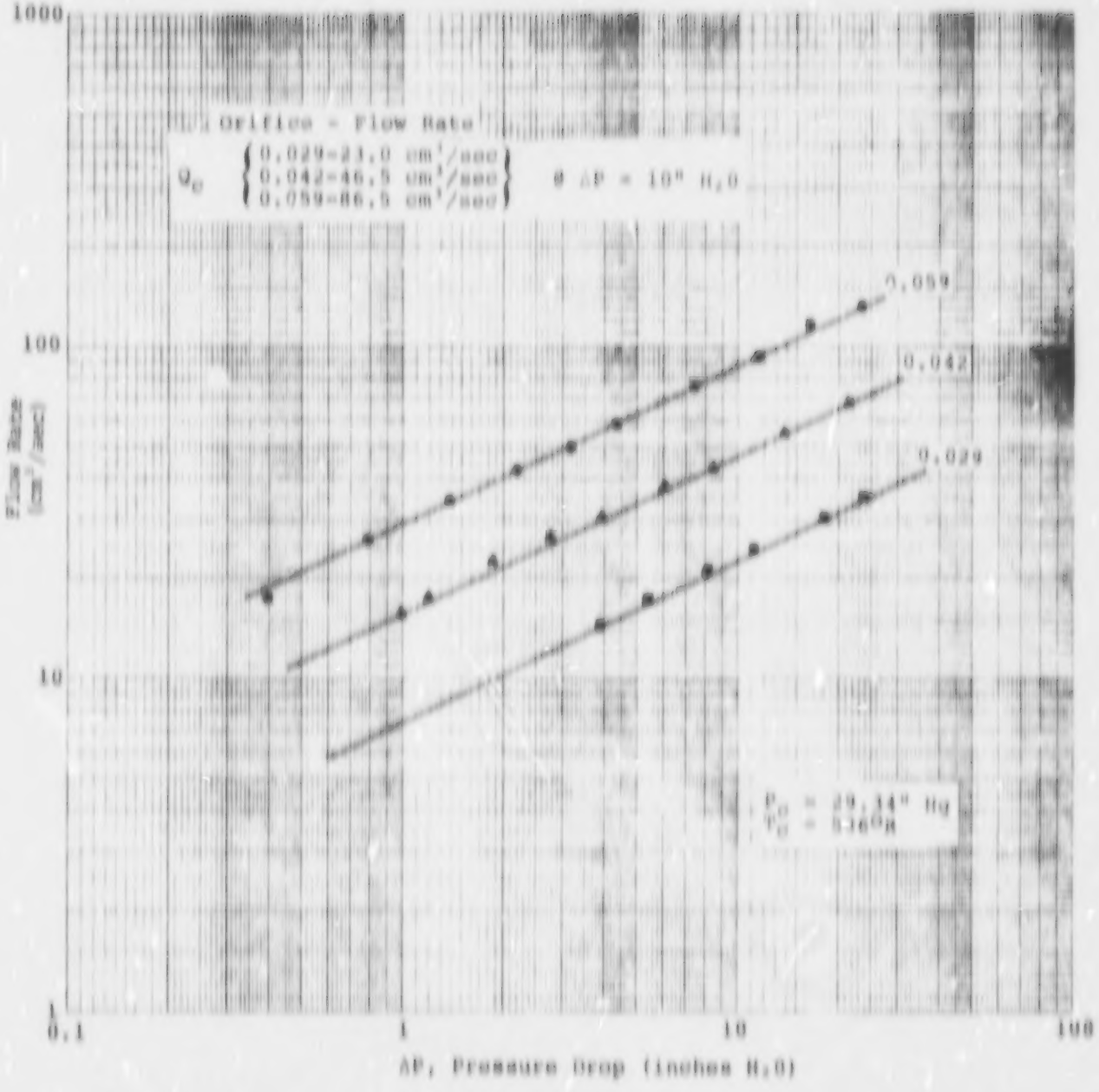


Figure 15. Sampling orifice calibration.

Q_m	= Flow rate indicated by the dry gas meter	ACFM
T_d	= Temperature of metered gas	^oR
T_g	= Flue gas temperature	^oR
P_d	= Pressure upstream of the meter referred to ambient	"dg
P_g	= Ambient stack pressure	"Hg
F_{H_2O}	= Volume fraction of water in flue gas	

If condensable vapors are not desired in the collection, and if the stack temperature is not high enough, auxiliary heating may be needed.

Heating the Impactor--

If flue streams above approximately 175°C (350°F), auxiliary heating is not usually required. The auxiliary heating is accomplished by wrapping the impactor with heater tape, which can be controlled by the temperature controller in the sampling case. A thermocouple placed in the impactor exit gas stream monitors the flue gas temperature immediately after it passes through the impactor. This temperature is needed for impactor cutpoint calculations. This thermocouple is connected to the temperature controller. If the impactor is wrapped with heater tape (also connected to the controller) the exit gas temperature can be controlled by simply setting the temperature controller to the desired temperature.

The impactor should be heated for at least 30 minutes (either in the duct or by external heater tape) before beginning sampling to insure that the entire impactor is at the desired temperature.

Taking the Sample--

After the impactor has reached its operating temperature, sampling can commence. If the impactor has been heated in the stack, the nozzle can be turned upstream and the correct flow rate quickly set. For short sampling times, typical of those that are necessary at control device inlets, this is especially important. If the impactor was heated outside the duct, some time should be allowed for the impactor temperature to come to an equilibrium with its new surroundings before the nozzle is turned upstream and sampling is begun. The flow rate should be maintained constant for the entire test to assure that the cutpoints do not change.

After the sample has been taken, the hose to the probe should be pinched off and the nozzle turned downstream before the impactor is removed from the duct. This procedure is especially important where there is a negative duct pressure. A negative duct pressure can cause a backflow through the impactor which might draw condensed water into the impactor from the probe and tubing. Therefore, care must be taken to insure that no gas flow through the impactor takes place except when sampling. It is also important to carefully remove the impactor from the duct to prevent any scraping or jarring and dislocation of particulate matter.

Disassembly of the Impactor

The post-test procedure is very important in obtaining useful results. The crucial part of this procedure is to make sure that the material on the collection substrates stays where it originally impacted, and that all particles not on these substrates are correctly cleaned onto the appropriate collection stage. A pair of fine tweezers and a small brush are essential in accomplishing this.

The first step in disassembly is to remove the inlet cap and the middle part of the housing. This exposes the stack of jet and collection plates. Remove the first jet plate to reveal the first collection substrate. All of the collected material above the first substrate should be brushed onto this substrate. Cleaning the nozzle completely is important, especially if it is a small bore nozzle. The inlet cap and both sides of the first jet stage should be cleaned and all the material placed on the first substrate. The first collection substrate can now be removed from the collection plate and stored in a suitable container to prevent any of the particulate matter from being lost. In lieu of a container, a foil square could be used. Use of a foil is a good method if there is a heavy loading of larger particles. All of the particulate matter in the nozzle and inlet cap can be brushed directly onto the foil, the collection substrate placed on the foil, and then the foil folded to prevent loss of any of the sample. This method though requires that the foil be preweighed with the collection substrate.

All of the material on the second jet plate is brushed onto the second collection substrate, and this substrate and the backup filter handled in a manner similar to that of the first substrate.

Once all the substrates have been removed and placed in their containers (foil or whatever), they should be placed in a desiccator and stored there for at least 24 hours. This desiccation brings the water content of the substrate to a level comparable to their initial level. After this desiccation period, the

substrates are weighed and the results recorded.

Cascade Impactor Data Reduction[5]

After an impactor run, it is necessary to obtain a particle size distribution from the mass loadings on each stage. The conditions at which the impactor was run determine the stage D_{50} cutpoints. Theoretical cutpoints can be calculated by an iterative solution of the following two equations:

$$D_{50} = 1.43 \times 10^{3} \left[\frac{\mu D_o^3 \rho_p P_s X(I)}{\rho_p Q_I P_o C \ 472.6} \right]^{\frac{1}{2}}$$

and

$$C = 1 + \frac{2L}{D_{50} \times 10^{4}} \left[1.23 + 0.41 \ EXP \left[\left[(-0.44 \ D_{50})/L \times 10^{-4} \right] \right] \right]$$

where

D_{50} is the stage cutpoint (μm),

μ = gas viscosity (poise),

D_o = stage jet diameter (cm),

P_s = local pressure at stage jet (atm),

ρ_p = particle density (gm/cm^3),

Q_I = impactor flow rate (cfm),

P_o = ambient pressure at impactor inlet (Atm),

C = Cunningham Correction Factor,

L = gas mean free path (cm), and

X(I) = number of holes per stage.

It is preferable however, to calibrate the impactor to determine the D_{50}'s, and in Figures 16 through 21, the calibration curves for the jet stage sets are given. These results were determined with an ammonium fluorescein aerosol which has a density of 1.35 gm/cm^3. By using the data from these curves and the theory presented by Ranz and Wong,[5] an equation can be developed to calculate the 50% collection efficiency size, or D_{50}, from the

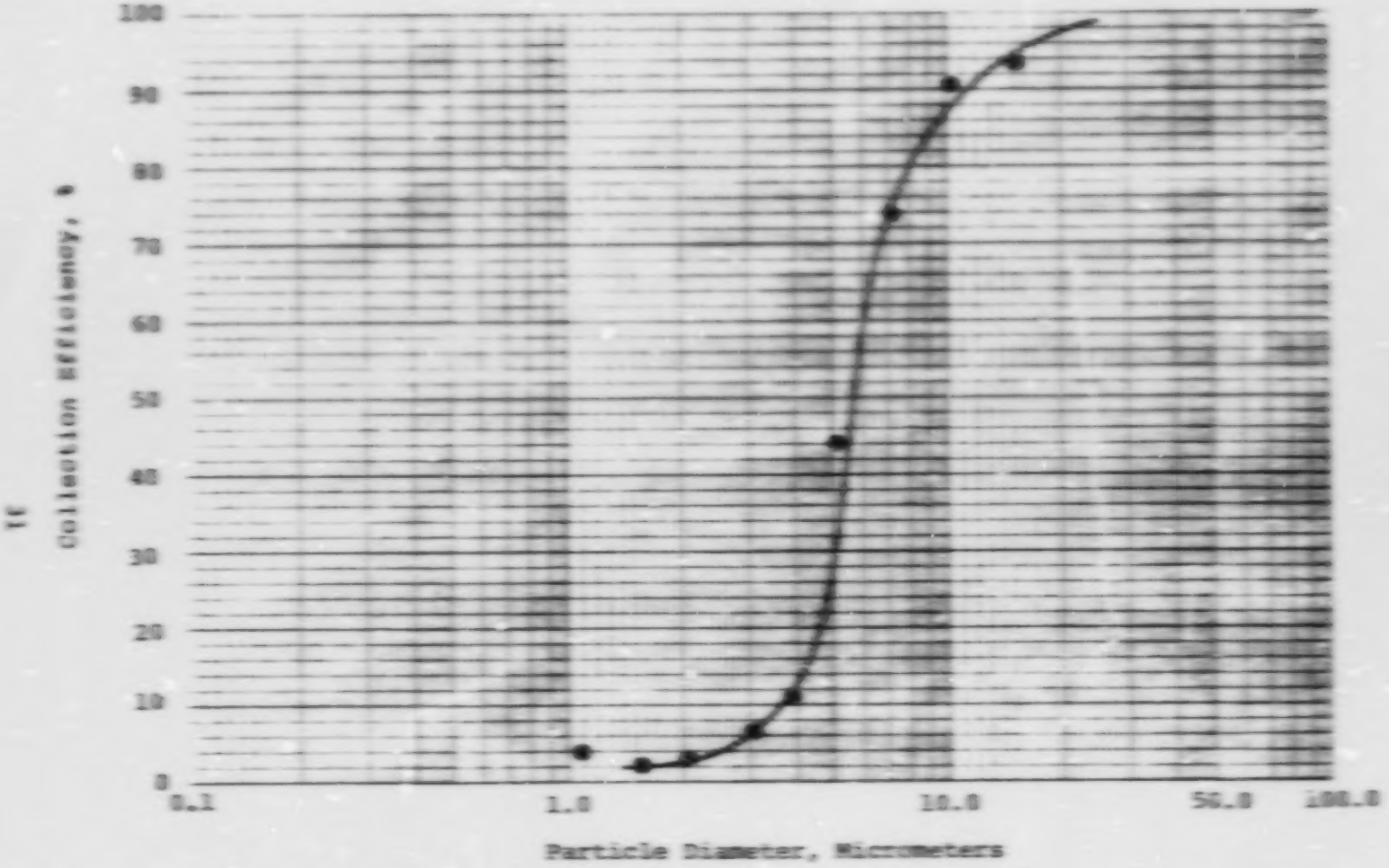


Figure 16. Collection efficiency vs. particle diameter for the PSC impactor: Plate Set 1 - Stage 1.

Calibration D_{50}: 5.5 μm, 94 cm^3/sec, ρ = 1.35 gm/cm^3
6.4 μm, 94 cm^3/sec, ρ = 1.00 gm/cm^3

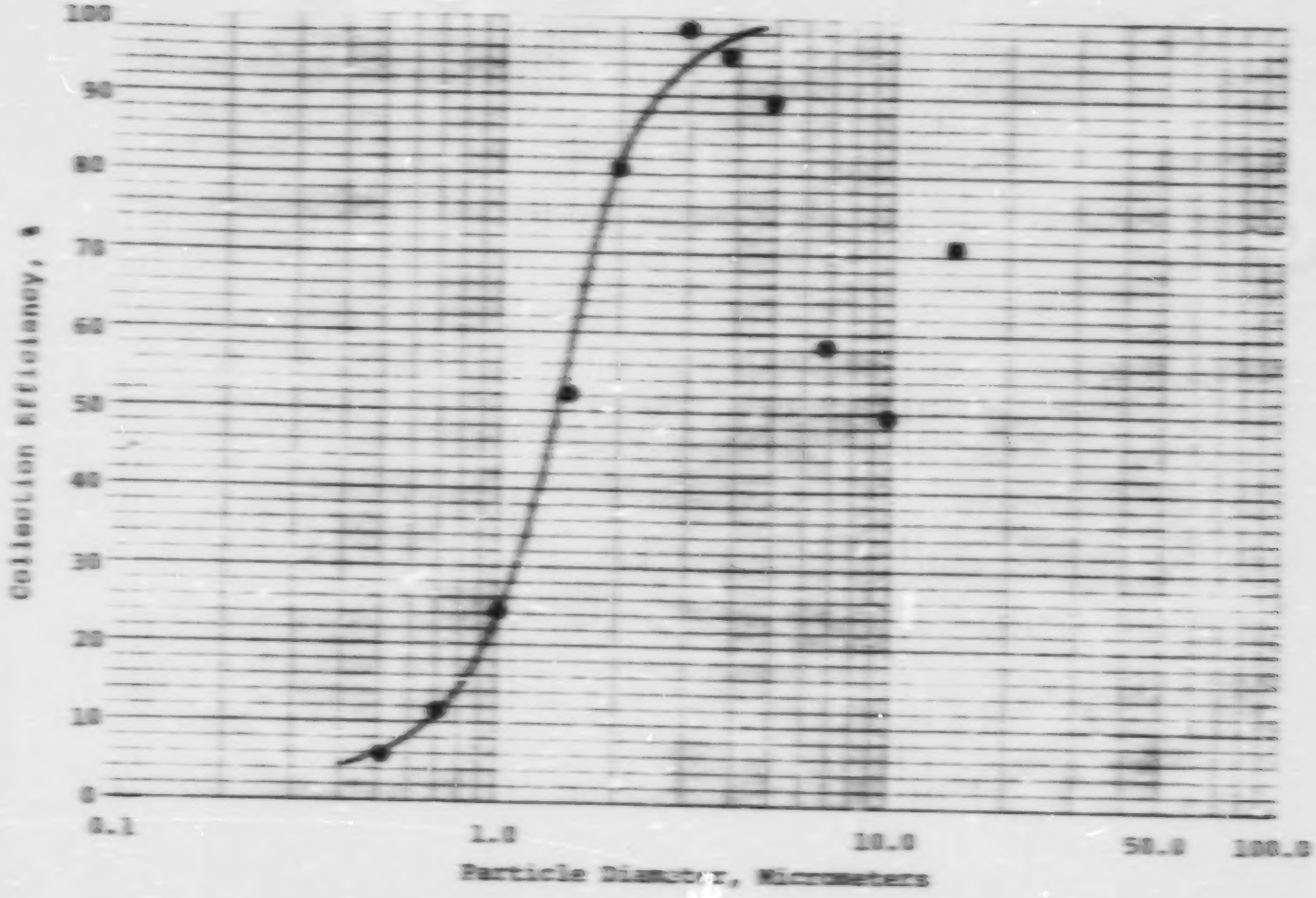


Figure 17. Collection efficiency vs. particle diameter for the PSC impactor: Plate Set 1 - Stage 2.

Calibration D_{50}: 1.40 μm, 94 cm^3/sec, ρ = 1.35 gm/cm^3
1.63 μm, 94 cm^3/sec, ρ = 1.00 gm/cm^3

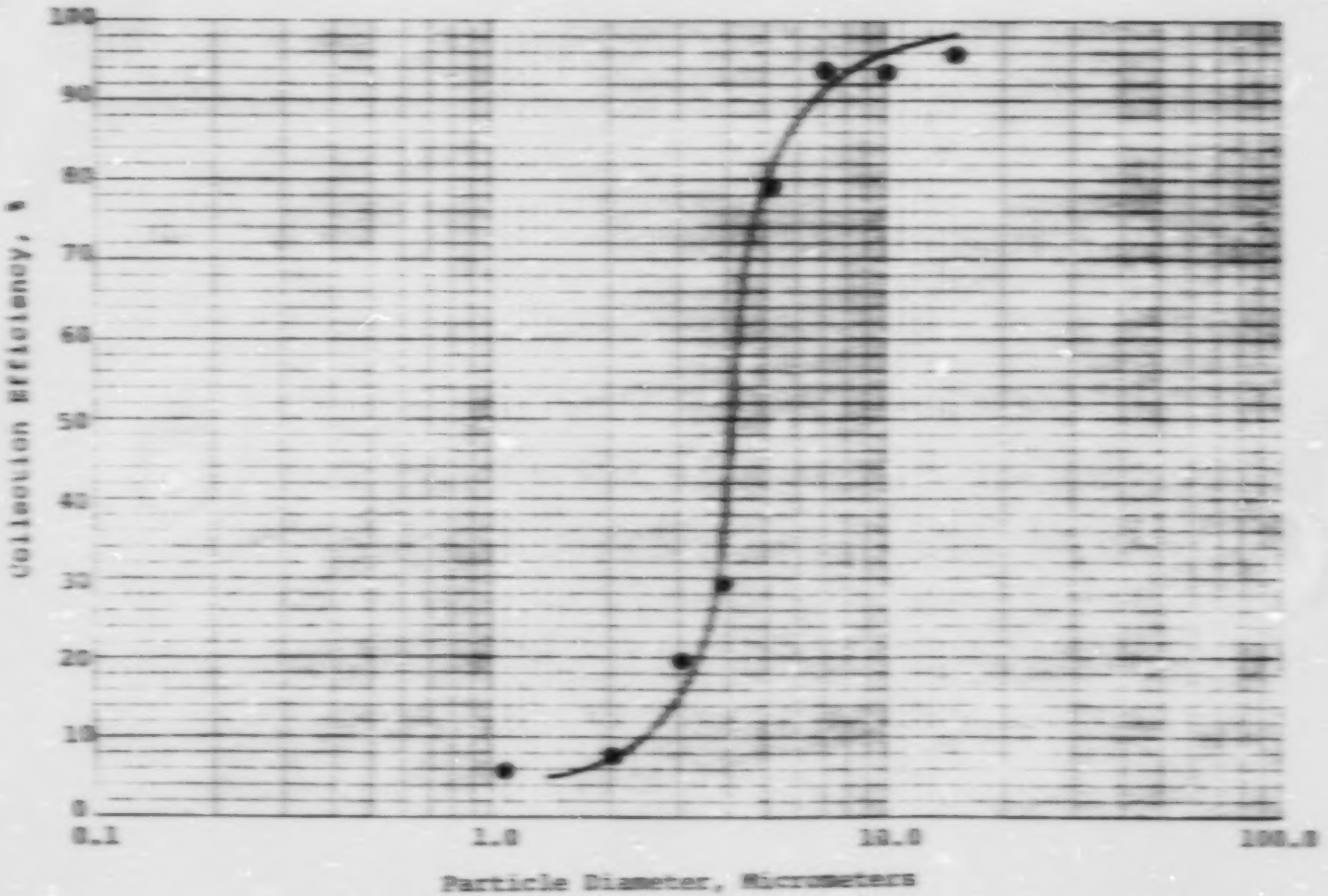


Figure 18. Collection efficiency vs. particle diameter for the PSC impactor: Plate Set 2 - Stage 1

Calibration D_{50}: 4.1 um, 47 cm^3/sec, ρ = 1.35 gm/cm^3
4.8 um, 47 cm^3/sec, ρ = 1.98 gm/cm^3

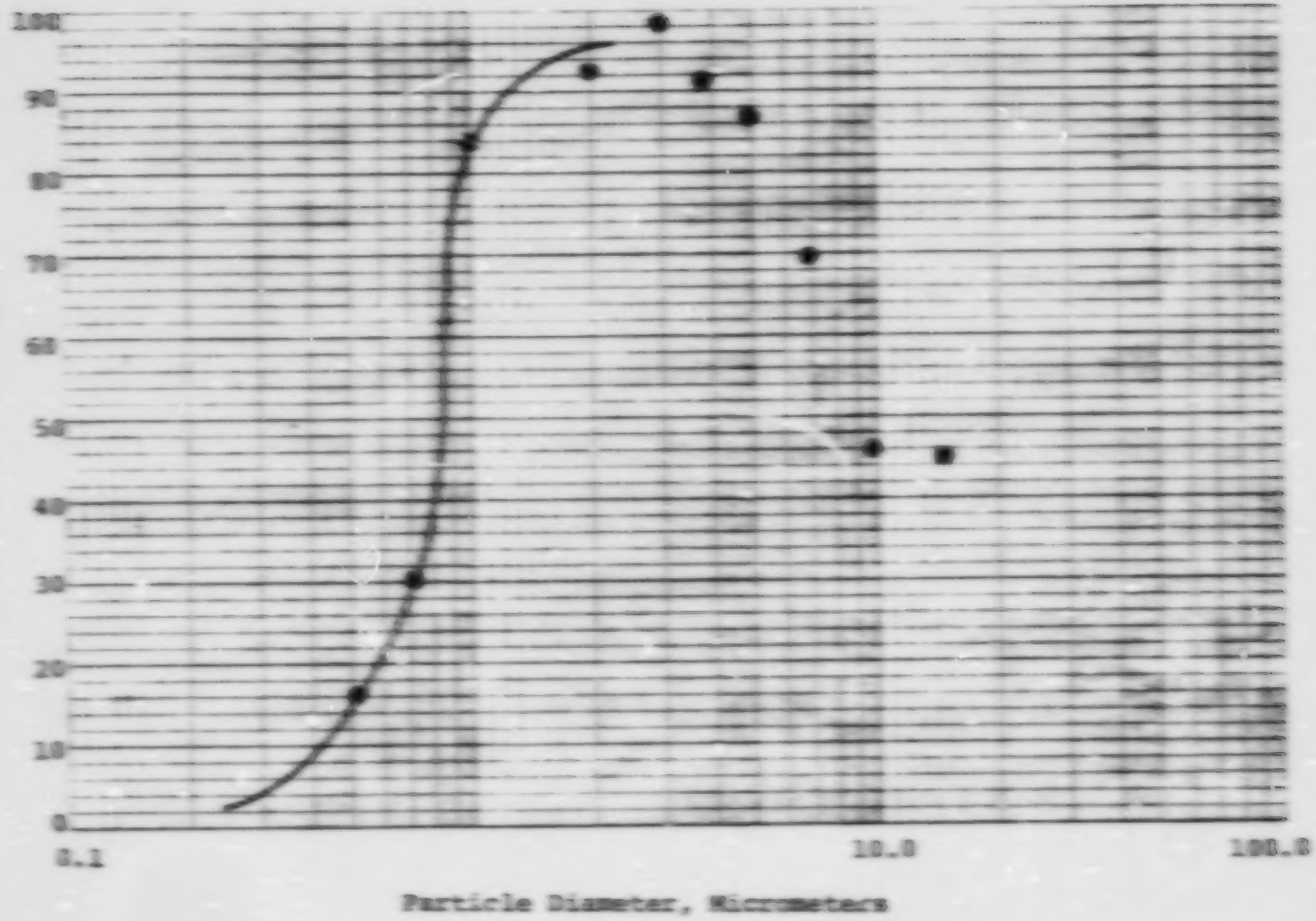


Figure 19. Collection efficiency vs, particle diameter for the PSC impactor: Plate Set 2 - Stage 2

Calibration D_{50}: 8.95 μm, 47 cm^3/sec, ρ = 1.35 gm/cm^3
8.99 μm, 47 cm^3/sec, ρ = 1.80 gm/cm^3

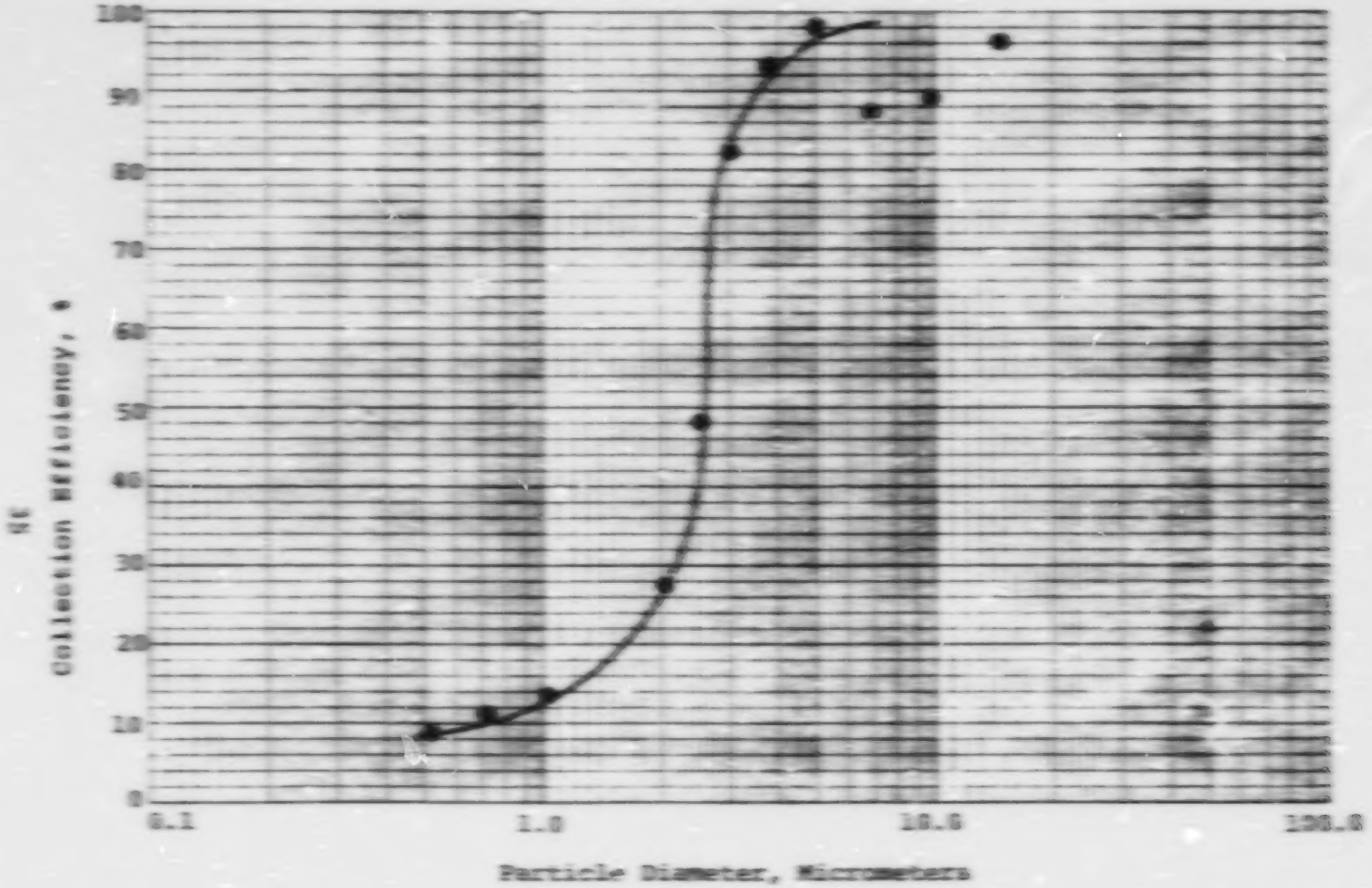


Figure 20. Collection efficiency vs. particle diameter for the PSC impactor: Plate Set 3 - Stage 1

Calibration D_{50}: 2.6 μm, 18.9 cm^3/sec, ρ = 1.35 gm/cm^3
3.8 μm, 18.9 cm^3/sec, ρ = 1.88 gm/cm^3

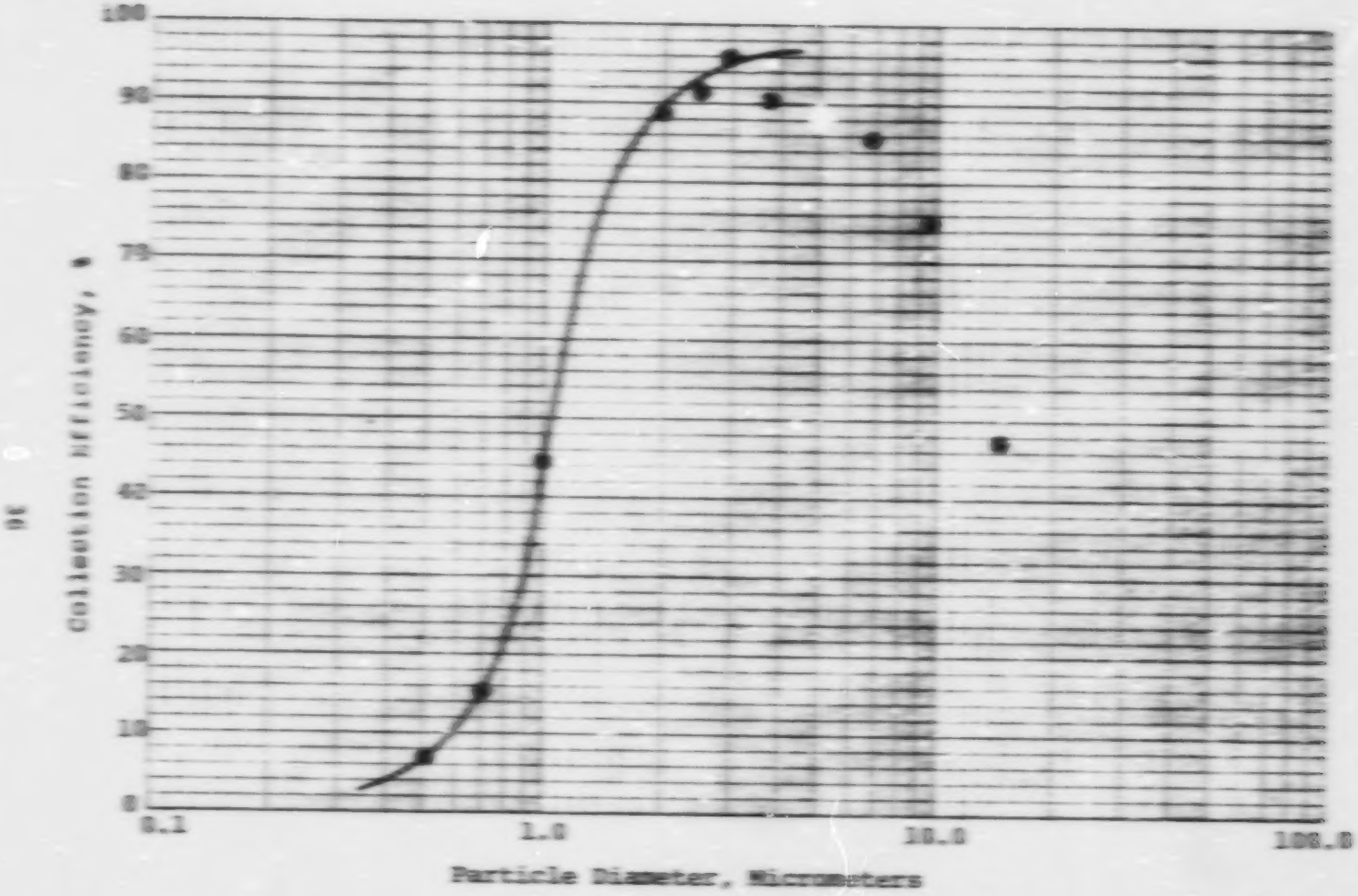


Figure 21. Collection efficiency vs. particle diameter for the PSC impactor: Plate Set 3 - Stage 2

Calibration D_{50}: 1.85 μm, 18.9 cm^3/sec, ρ = 1.35 gm/cm^3
1.22 μm, 18.9 cm^3/sec, ρ = 1.00 gm/cm^3

calibration curves for the range of sampling conditions which are normally encountered in source testing. Rans and Wong studied the effects of various forces on a particle which cause it to move through a gas stream onto a collection body. For inertial impaction, these forces can be presented in a dimensionless parameter ψ given by

$$\psi = C_p F D_p^2 / 4.5 \pi \mu D_c^3$$

where C = Cunningham Correction Factor, dimensionless,

ρ_p = Particle density, gm/cm^3,

F = Gas flow rate through impactor, cm^3/sec,

D_p = Particle diameter, cm,

μ = Gas stream viscosity, gm/cm sec, and

D_c = Diameter of jet, cm

ψ is the ratio of the stopping distance of a particle with velocity of $V_o = 4F/\pi D_c^2$ to the jet diameter, D_c. By holding all parameters in the equation constant except for D_p, as is done in calibrating the impactor, a plot of collection efficiency versus $\sqrt{\psi}$ can be obtained. From this graph, the value of $\sqrt{\psi}$ at which the collection efficiency is 50% can be found. If this value for $\sqrt{\psi_{50}}$ is used in the equation for ψ, the D_{50} or cut-equation is obtained by solving for D_{p50}.

$$D_{p50} = \left(\frac{4.5 \pi \mu D_c^3}{C \rho_p F}\right)^{1/2} (\psi_{50})^{1/2}$$

This equation will furnish the correct stage D_{50} point for sampling conditions different from those at calibration. Figures 22-24 show the laboratory calibration data presented in this form for each of the three plate sets. These calibration curves have been used to obtain values of $\sqrt{\psi_{50}}$ for each stage. These constants are given in Table 1.

Table 2 contains values for the viscosity of air at temperatures between 10°C and 300°C and for gas water content by volume from 0% to 10%.[3] These values are to be used in the HP-65 program for calculating the impactor stage D_{50}.

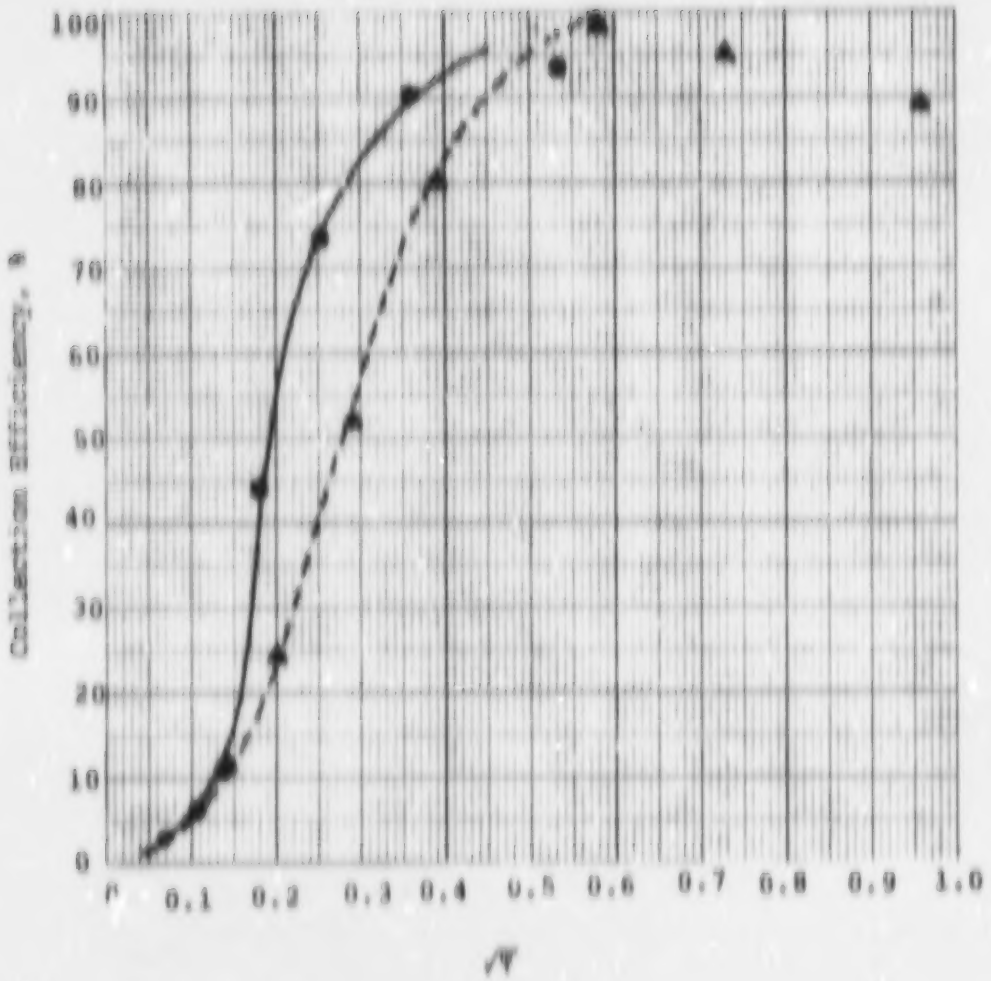


Figure 22. Collection Efficiency vs. $\sqrt{\Psi}$
PSC Impactor - Plate Set 1
Constant Flowrate and Variable Particle Size

● Stage 1
▲ Stage 2

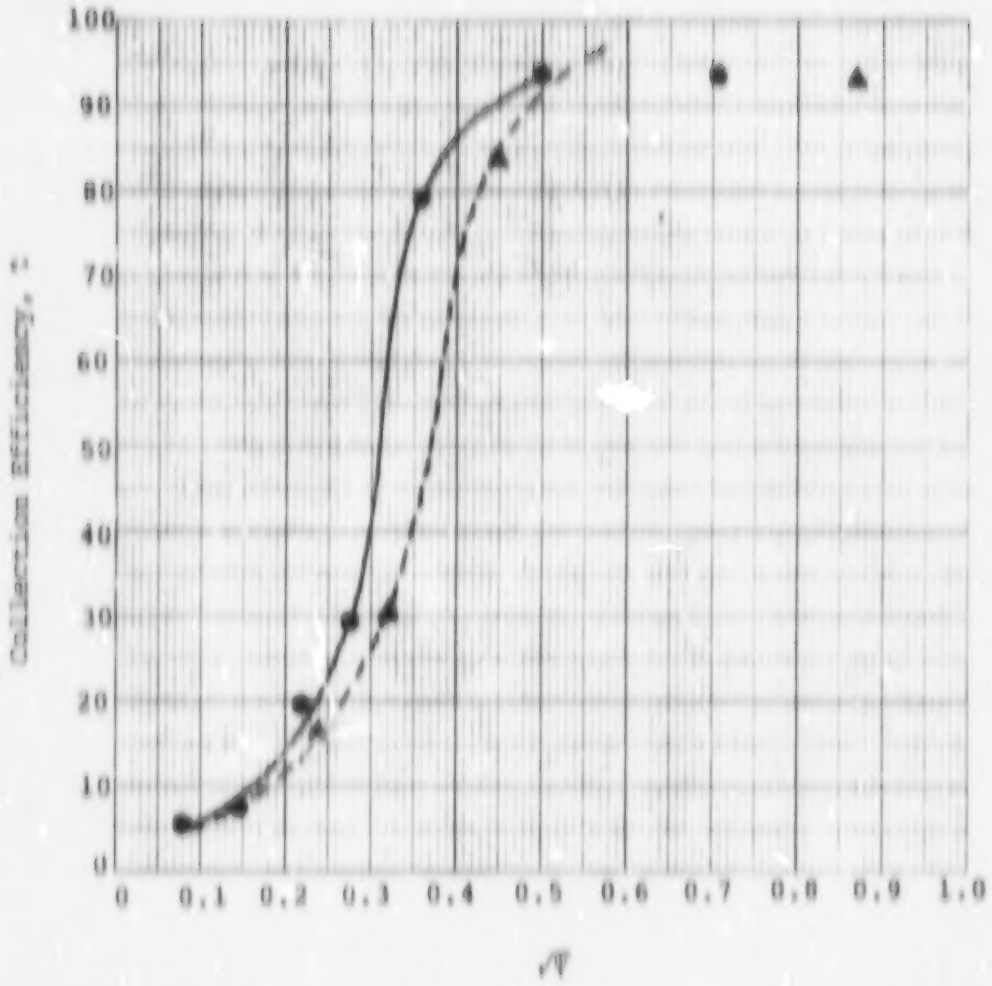


Figure 23. Collection Efficiency vs. $\sqrt{\Psi}$
PBC Impactor - Plate Set 2
Constant Flowrate and Variable Particle Size

● Stage 1
▲ Stage 2

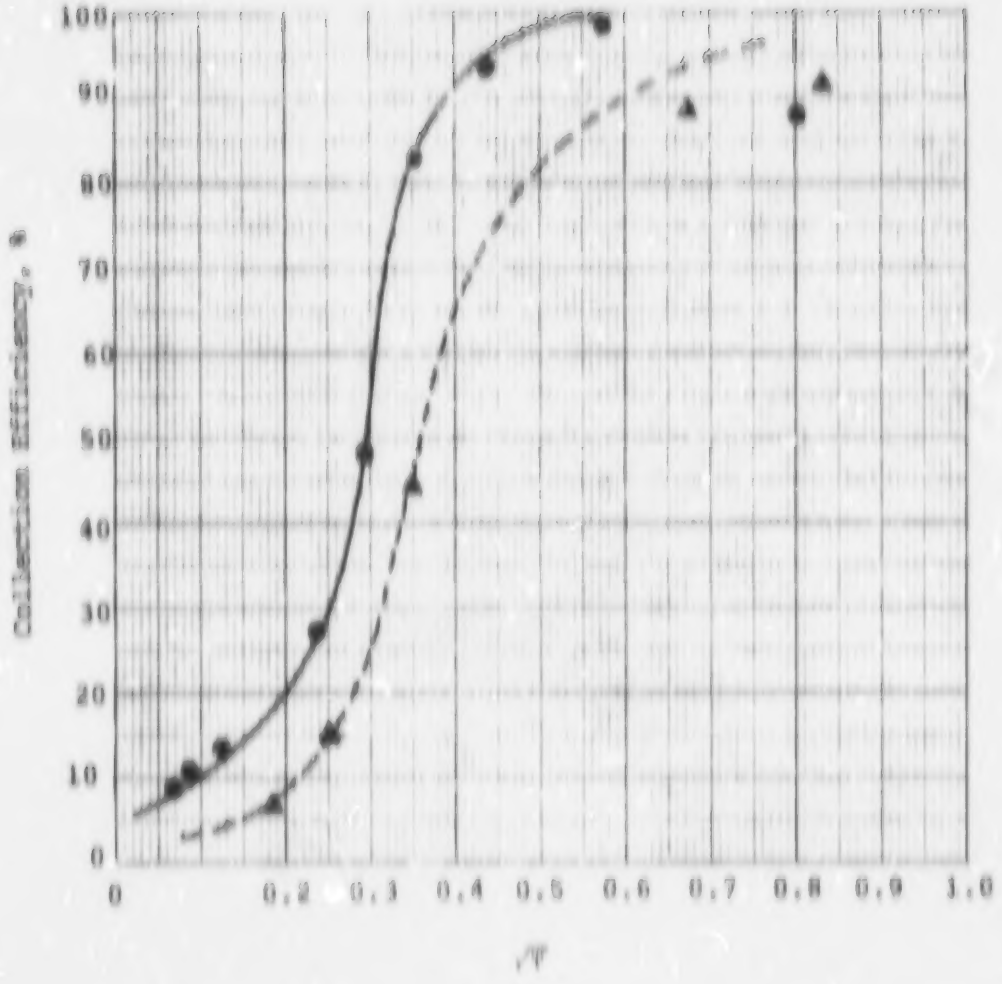


Figure 24. Collection Efficiency vs. $\sqrt{\Psi}$
PSC Impactor - Plate Set 3
Constant Flowrate and Variable Particle Size

● Stage 1
▲ Stage 2

TABLE 2. VISCOSITY OF AIR VS. H_2O CONTENT

$10^{\circ}C - 100^{\circ}C$

°C	% H_2O										
	0	1	2	3	4	5	6	7	8	9	10
10	1.767	1.758	1.748	1.739	1.730	1.720	1.712	1.702	1.693	1.684	1.675
20	1.813	1.803	1.792	1.783	1.774	1.765	1.755	1.746	1.737	1.728	1.719
30	1.854	1.844	1.835	1.826	1.817	1.808	1.799	1.790	1.780	1.771	1.762
40	1.901	1.897	1.878	1.869	1.860	1.850	1.841	1.832	1.823	1.814	1.805
50	1.938	1.929	1.920	1.911	1.902	1.892	1.883	1.874	1.865	1.856	1.847
60	1.979	1.970	1.961	1.952	1.943	1.934	1.925	1.916	1.907	1.898	1.888
70	2.025	2.015	2.005	1.995	1.984	1.975	1.966	1.957	1.948	1.939	1.930
80	2.059	2.050	2.042	2.033	2.024	2.015	2.006	1.997	1.988	1.979	1.971
90	2.096	2.090	2.081	2.072	2.063	2.054	2.046	2.037	2.028	2.019	2.010
100	2.137	2.129	2.120	2.111	2.102	2.093	2.085	2.076	2.067	2.059	2.049
110	2.175	2.167	2.158	2.149	2.140	2.132	2.123	2.114	2.105	2.097	2.088
120	2.223	2.209	2.195	2.189	2.179	2.169	2.161	2.153	2.143	2.135	2.126
130	2.258	2.241	2.232	2.224	2.215	2.207	2.198	2.189	2.181	2.171	2.164
140	2.296	2.277	2.269	2.260	2.252	2.242	2.235	2.226	2.219	2.209	2.201
150	2.331	2.323	2.304	2.296	2.288	2.279	2.271	2.262	2.254	2.245	2.237
160	2.356	2.348	2.339	2.331	2.323	2.315	2.306	2.298	2.289	2.281	2.273
170	2.398	2.382	2.374	2.366	2.358	2.349	2.341	2.333	2.325	2.317	2.309
180	2.424	2.416	2.408	2.400	2.392	2.383	2.375	2.367	2.359	2.351	2.343
190	2.457	2.449	2.441	2.433	2.425	2.417	2.409	2.401	2.393	2.385	2.377
200	2.489	2.482	2.474	2.466	2.458	2.450	2.442	2.434	2.426	2.418	2.410
210	2.521	2.513	2.506	2.498	2.490	2.482	2.475	2.467	2.459	2.451	2.443
220	2.552	2.545	2.537	2.530	2.522	2.514	2.507	2.499	2.491	2.483	2.475
230	2.583	2.575	2.568	2.560	2.553	2.545	2.538	2.530	2.523	2.515	2.507
240	2.613	2.606	2.598	2.591	2.583	2.576	2.569	2.562	2.554	2.546	2.539
250	2.642	2.635	2.628	2.621	2.613	2.606	2.599	2.592	2.584	2.577	2.570
260	2.671	2.664	2.657	2.650	2.643	2.636	2.629	2.622	2.614	2.607	2.600
270	2.699	2.692	2.685	2.678	2.671	2.663	2.657	2.650	2.643	2.636	2.629
280	2.727	2.720	2.713	2.706	2.700	2.693	2.686	2.679	2.672	2.665	2.658
290	2.754	2.747	2.740	2.734	2.727	2.720	2.714	2.707	2.700	2.694	2.687
300	2.780	2.773	2.767	2.761	2.754	2.748	2.741	2.734	2.728	2.721	2.715

$\times 10^{-5}$ poise

The most feasible way to calculate these cutpoints is to write a computer program. Otherwise, a slow and tedious process results. The size parameter reported can be either aerodynamic diameter, that is, diameter based on the behavior of unit density particles, or approximate physical diameter, based on the estimate of the true particle density. In either case, the particles are assumed to be spherical.

A program for the HP-67 has been written to calculate the D_{50} cutpoints for each of the jet plate sets. The program sheet gives a breakdown of the parameters needed to calculate the cutpoints. Once the D_{50} cutpoints have been calculated, the particle size distribution may be presented on a differential or cumulative basis.

Differential Particle Size Distributions--

For the purpose of analysis, the assumption is made that all of the mass caught on an impaction stage consists of material having diameters equal to, or greater than the D_{50} for that stage. For the first stage, it is assumed that all the material caught has diameters greater than, or equal to, the D_{50} for that stage, but less than the largest particle size that has been sampled.

Because the intervals between the stage D_{50}'s are logarithmically related, and to minimize scaling problems, the differential particle size distributions are plotted on log-log or semilog paper with

$$\frac{M_n}{\Delta (\log D)}$$

as the ordinate and log D_{geo} as the abscissa. (D_{geo} is the geometric mean of D_1 and D_2; $D_{geo} = \sqrt{D_1 D_2}$.) The mass on stage "n" is designated by M_n. The Δ (log D) associated with M_n is $\log (D_{50})_{n+1} - \log (D_{50})_n$. The total mass having diameters between $(D_{50})_m$ and $(D_{50})_n$ is equal to the area under the curve; i.e.,

$$\text{Mass} = \sum_{t=m}^{n} \frac{M_t}{\log (D_{50})_{t+1} - \log (D_{50})_t} \cdot \left[\log (D_{50})_{t+1} - \log (D_{50})_t\right]$$

or

$$\text{Mass} = \left[\int_{D_m}^{D_n} \frac{dM}{d (\log D)}\right] \cdot \left[d (\log D)\right]$$

for a near continuum.

The procedure outlined above is used to construct a histogram. In practice, a smooth curve is frequently drawn through the points, yielding an approximation to the real particle size distribution. Such a curve is needed to calculate fractional efficiencies of control devices if the D_{50}'s differ between inlet and outlet measurements. The accuracy of the approximation is limited by the number of points, and by the basic inaccuracy of neglecting the nonideal behavior of the impactors, especially overlapping collection efficiencies for adjacent stages.

Cumulative Particle Size Distributions--

The data may be presented on a cumulative basis by summing the mass on all the collection stages and back-up filter, and plotting the fraction of the mass below a given size, versus size. This is frequently done on special log-probability paper. This paper is especially convenient for log normal distributions, but semi-log paper may be preferable for interpretation, especially if the distribution is not log normal. In general, cumulative distributions are more difficult to interpret than differential plots. The abscissa is the logarithm of the particle diameter, and the ordinate is the percentage smaller than this size. The value of the ordinate at a given $(D_{50})_n$ would be

$$\text{Percent less than stated size} = \frac{\sum_{t=0}^{t=n} M_t}{\sum_{t=0}^{N} M_t} \times 100\%$$

or

$$\text{Cumulative mass less than stated size} = \sum_{t=0}^{t=n} M_t$$

where

t = o corresponds to the filter,

t = n corresponds to the stage under consideration, and

t = N corresponds to the coarsest jet or cyclone.

Alternately, an analytical curve might be fitted to the cumulative distribution obtained above, and values of dM/d(logD) obtained by differentiation of the analytical expression.

A program for the HP-65 has been written to calculate the cumulative particle size distribution. This is given in the program sheet.

Sample Calculations with the HP-65 Programs

Sampling Orifice Pressure Drop Calculation--

This program calculates the pressure drop across a particular sampling orifice for a desired impactor flow rate. The following data are required:

1. Desired sampling flow rate (cm^3/sec).

2. Calibration flow rate at 10" H_2O (cm^3/sec).

3. Volume fraction of water in the flue gas.

4. Ambient pressure at the impactor inlet ("Hg).

5. Ambient pressure when orifice was calibrated ("Hg).

6. Orifice temperature when sampling (°C).

7. Impactor gas exit temperature (°C).

8. Orifice temperature when orifice was calibrated (°C).

The calibration information for the orifice is found on the orifice calibration sheet. The other data are for the particular stack conditions under consideration.

For the following sample calculation, the orifice information has been taken from the calibration sheet and the stack conditions assumed (for a typical source). They are listed below:

1. Desired flow rate = 50 cm/sec,

2. Calibration flow rate = 46.5 cm/sec.

3. Volume fraction of water = 0.10.

4. Ambient pressure at impactor inlet = 28.5 "Hg.

5. Ambient pressure at calibration = 29.34 "Hg.

6. Orifice temperature when sampling = 29°C.

7. Gas exit temperature = 200°C.

8. Orifice temperature when calibrated = 24.5°C.

When these conditions are inputed to the calculator in the sequence indicated on the user instruction sheet and the program is run, a value for the orifice pressure drop will appear in the x-register. For the above conditions, the orifice pressure drop is

$$\Delta P = 3.65" H_2O$$

Particle Size Distribution Calculation--

This program calculates the cumulative mass loading for the two cutpoints and the total mass loading in both actual cubic meters and standard dry cubic meters. Also calculated is the cummulative percent for the stages. Necessary inputs are as follows:

1. Collected mass on first stage (milligrams).

2. Collected mass on second stage (milligrams).

3. Collected mass on filter (milligrams).

4. Sampling flow rate (cm^3/sec).

5. Sampling duration (minutes).

6. Gas temperature (°C).

7. Ambient pressure at impactor inlet ("Hg).

8. Volume fraction of water.

Assuming typical field test data (given below) and inputing the data into the program, the particle size distribution can be found.

1. Mass on first stage = 12.0 mg.

2. Mass on second stage = 7.0 mg,

3. Mass on filter = 8.5 mg,

4. Flow rate = 50 cm^3/sec,

5. Sampling duration = 90 min,

6. Gas temperature = 200°C,

7. Impactor ambient pressure = 28.5 "Hg,

8. Volume fraction of water = 0.10,

Total mass loading = 101.9 mg/ACM = 190.5 mg/DNCM*

Cumulative mass loading to first stage cutpoint = 57.4 mg/ACM = 107.4 mg/DNCM,

Cumulative mass loading to second stage cutpoint = 31.5 mg/ACM = 58.9 mg/DNCM,

Cumulative percent to first stage = 56.4%,

Cumulative percent to second stage = 30.9%,

Impactor Stage Cutpoint Calculation--

This program calculates the cutpoint for a particular jet stage for a given impactor flow rate and flue conditions. The following data are used:

1. Flue gas viscosity (poise),

2. Ambient pressure at impactor inlet ("Hg),

3. Impactor exit gas temperature (°C),

4. Jet diameter (cm),

5. Number of jets,

6. Particle density (gm/cm^3),

7. Impactor flow rate (cm^3/sec),

8. Jet plate constant,

*Dry Normal Cubic Meter - 760, mmHg, 21.1°C, dry.

The flue gas viscosity can be taken from the table of viscosities given. The jet plate information (jet diameter and number of jets) is found in Table 1. The jet plate constant is located on the HP-65 program form.

Selecting, for example, the jet plate designed for a nominal cutpoint of 5 microns at a flow rate of 47 cm^3/sec, typical values for the program are as follows (assuming typical stack conditions):

1. Flue gas viscosity = 2.225×10^{-5} poise.
2. Ambient pressure at impactor inlet = 30.42 "Hg.
3. Exit gas temperature = 146°C.
4. Jet diameter = 0.167 cm.
5. Number of jets = 10.
6. Particle density = 1.00 gm/cm^3.
7. Impactor flow rate = 57 cm^3/sec.
8. Jet plate constant = 1.54×10^4.

For these values the cutpoint for this jet stage is

$$D_{50} = 5.18 \text{ micrometers.}$$

Field Testing of the PSC Impactor

Bull Run Steam Plant--

In March, 1975 the first field test of the PSC impactor took place at the TVA Bull Run Steam Plant in Oak Ridge, Tennessee. The tests were conducted on the outlet duct of Precipitator A about 20 feet upstream from the stack. Concurrently with each test a Brink Cascade Impactor was run to obtain a comparative size distribution. The mass loading at this point was approximately 2.3 grams per actual cubic meter (1.0 grain per actual cubic foot) which is high for a coal-fired boiler precipitator outlet. The high mass loading limited the sampling time of the impactor considerably.

All three jet sets of the PSC impactor were tested. In these tests, jet plate set I was run at 94 cm^3/sec (0.2 cfm), jet plate set II at 47 cm^3/sec (0.1 cfm), and jet plate set III at 19 cm^3/sec (0.04 cfm). A 2.5 mm nozzle was required in order to obtain isokinetic sampling for the 94 cm^3/sec flow rate, a 1.75 mm nozzle for the 47 cm^3/sec, and a 1.0 mm nozzle for the 19 cm^3/sec. However, the smallest nozzles were 2.5mm for both the two-stage impactor and the Brink Cascade Impactor which was run at 14 cm^3/sec. Thus, the two-stage impactor with jet plate set I sampled isokinetically while the other two jet plate sets and the Brink sampled anisokinetically.

The tests were performed on three days. On the first day jet plate set I was tested, on the second day plate sets II and III, and on the third day plate sets I and III. A Brink Cascade Impactor was run each day in the same port and at the same depth. Table 1 shows the pertinent data for each test including the stage weight gains. During the first two days Teflon collection substrates were used and on the last day Gelman Type A Glass Fiber substrates were used. From visual inspection, each substrate appeared to have good particle retention qualities but the Teflon was easier to remove after sampling without collected dust being dislodged. Sampling times were undesirably short due to the high particulate grain loading.

Figures 25, 26, and 27 show the results of this preliminary test for each day of testing. In Figure 25 the curve for jet plate set I is lower in total loading than the Brink. This is expected since the Brink sampled anisokinetically and collected a greater than normal quantity of large particles. The plate set I test sampled isokinetically. The Brink test should be reliable below 2 or 3 microns however and it can be seen that the plate set I curve is above the Brink indicating possible bounce and reentrainment. In Figure 26 agreement in total loading between the Brink and plate set III is seen when both types of impactor were operated anisokinetically at very nearly the same

TABLE 3. TWO-STAGE IMPACTOR TEST DATA

	DATE	3/11/75	3/12/75	3/12/75	3/13/75	3/11/75
	PORT	2	2	2	2	2
"Hg	Amb. Pres.	29.31	28.69	30.99	29.00	29.09
"H_2O	Stack Pres.	-1.6	-1.2	-1.2	-1.6	-1.0
m/sec	Gas Velocity	20	20	20	20	20
"H_2O	Orifice ΔP	5.7	5.1	3.8	3.8	5.7
in.	Orifice I.D.	.059	.042	.029	.029	.059
"Hg	Imp. ΔP	0.7	0.4	0.2	0.2	0.7
°C	Imp. Temp.	143	138	160	149	138
°C	G.M. or Orifice	13	19	17	18	18
cm^3/sec	Flow rate	99	47	20	20	98
	% H_2O	7.5	7.5	7.5	7.5	7.5
	Start Time	4:15	12:45	3:15	11:50	2:50
Min.	Duration	3	6	15	10	3
mm	Nozzle	2.5	2.5	2.5	2.5	2.5
	Impactor Plate Set	I	II	III	III	I
	STAGE WEIGHT GAIN					
mg	1	7.78	12.46	13.18	63.14	27.14
mg	2	8.16	5.46	7.66	14.26	20.14
mg	Filter	2.90	3.42	5.20	9.54	7.62

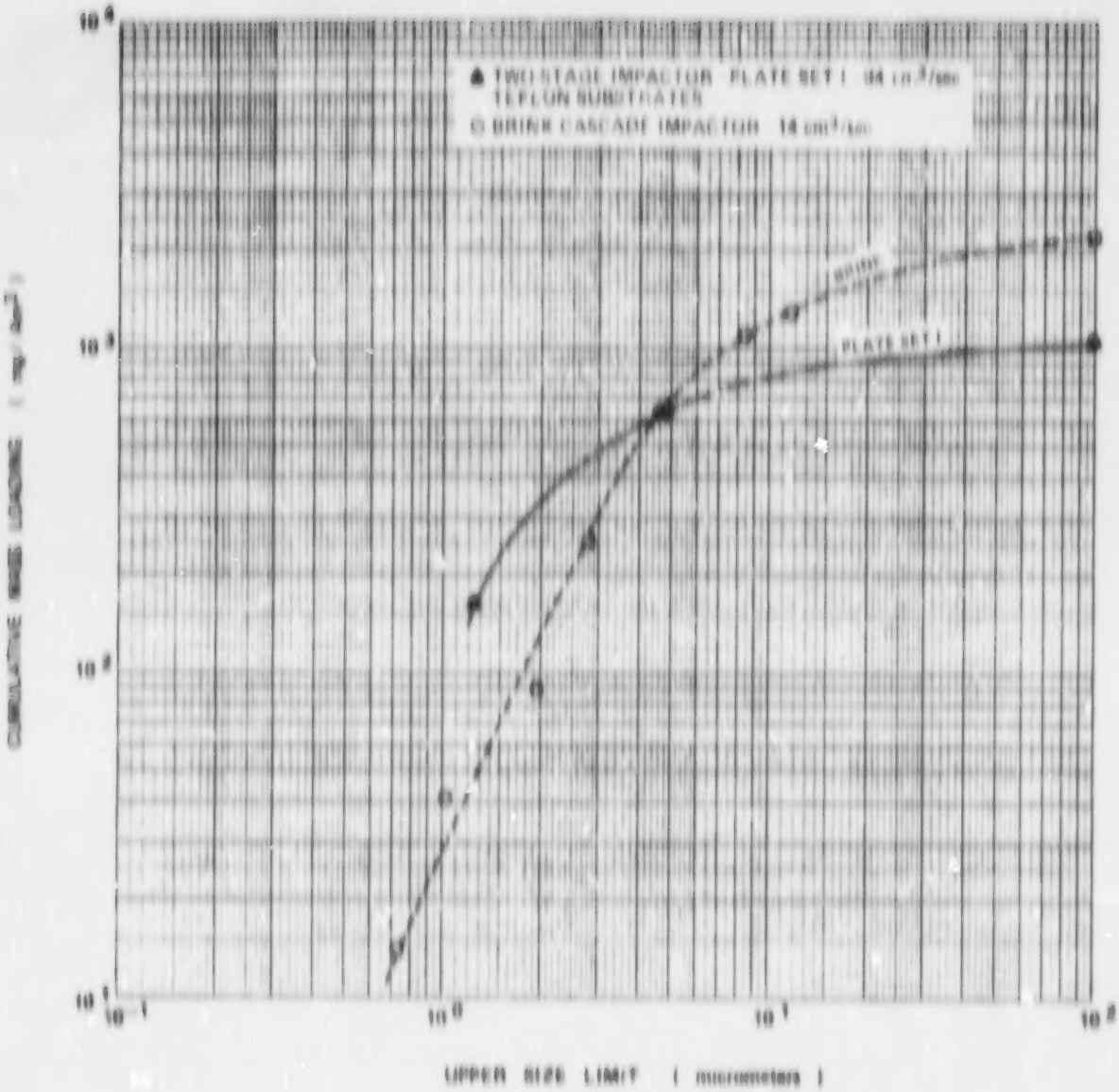


Figure 25. Cumulative Mass Loading versus Particle Diameter
March 11, 1975

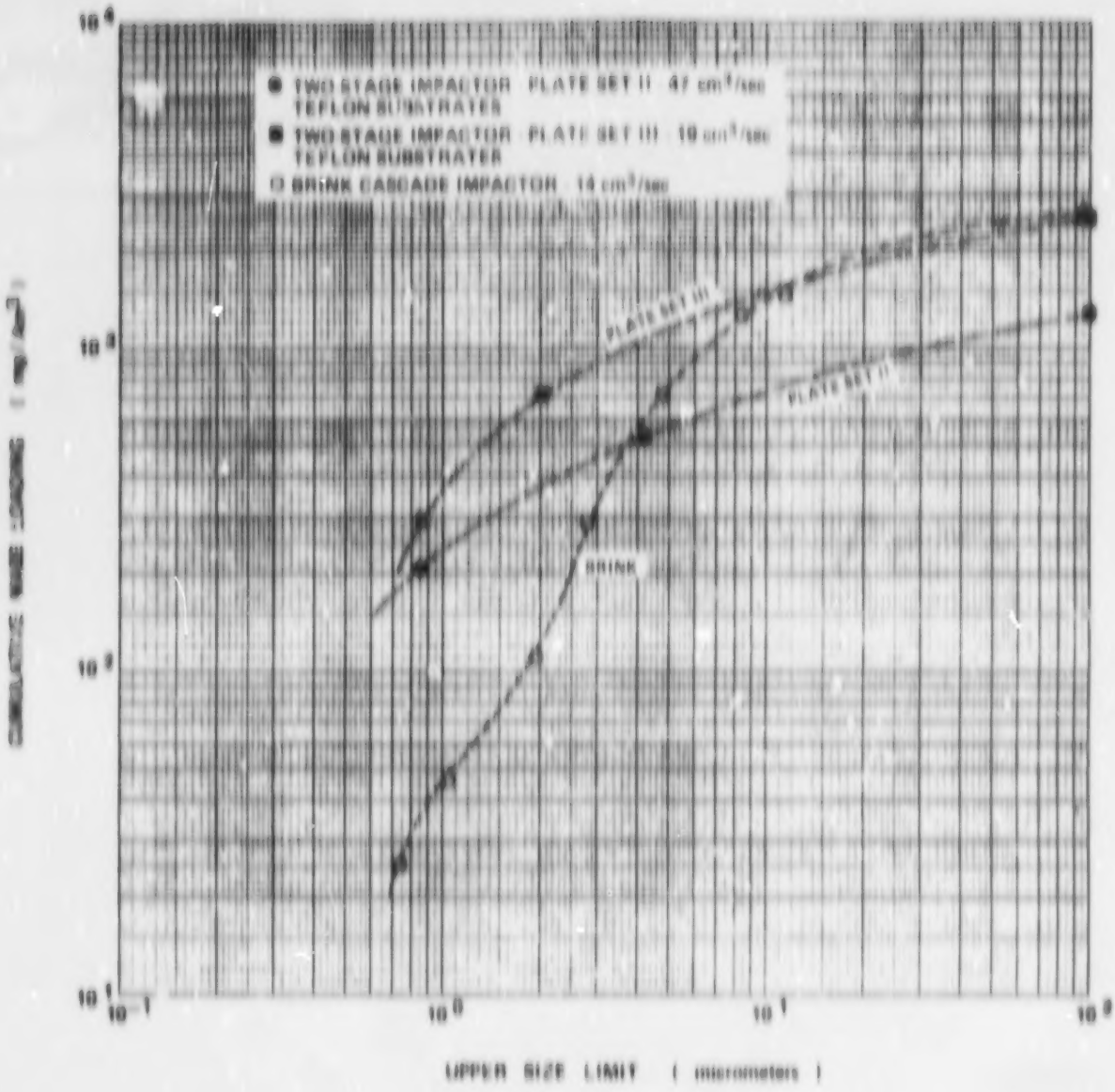

TWO STAGE IMPACTOR - PLATE SET II - 47 cm³/sec
TEFLON SUBSTRATES
TWO STAGE IMPACTOR - PLATE SET III - 19 cm³/sec
TEFLON SUBSTRATES
BRINK CASCADE IMPACTOR - 14 cm³/sec
PLATE SET III
PLATE SET II
BRINK
UPPER SIZE LIMIT (micrometers)

Figure 26. Cumulative Mass Loading versus Particle Diameter
March 12, 1975

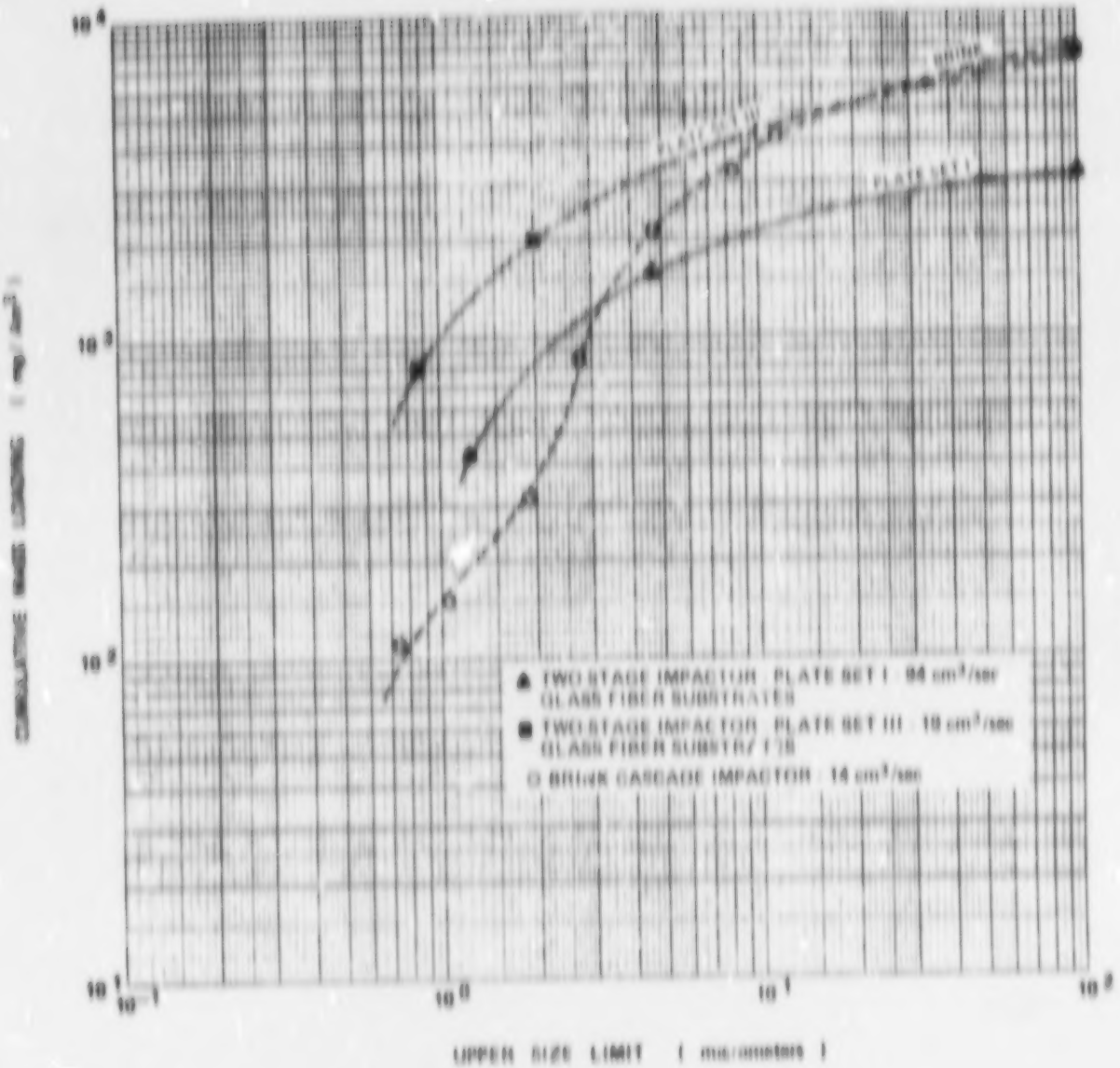

TWO STAGE IMPACTOR - PLATE SET I - 94 cm³/sec
GLASS FIBER SUBSTRATES
TWO STAGE IMPACTOR - PLATE SET III - 19 cm³/sec
GLASS FIBER SUBSTRATES
O BRINK CASCADE IMPACTOR - 14 cm³/sec
UPPER SIZE LIMIT (micrometers)

Figure 27. Cumulative Mass Loading versus Particle Diameter
March 13, 1975

conditions. The curve for plate set II is lower because this set was used nearer isokinetic conditions. In both cases the submicron end of the cumulative size distribution is higher than the Brink, perhaps indicating passage of particles to lower stages which should have remained on an earlier stage. Figure 27 shows results similar to Figure 26.

Gorgas Steam Plant--

On June 25-26, 1975, a test of the two-stage impactor was performed at Alabama Power's Gorgas Steam Plant. Sampling was conducted at the outlet duct of the Unit 10 coal boiler, downstream of the precipitator. Each of the three pairs of jet plates were used during this series of tests. An Andersen Stack Sampler was run simultaneously with the two-stage impactor to obtain a comparable size distribution. Glass fiber substrates were used in both impactors for all tests. The two-stage impactor and Andersen were located at the same vertical level in the duct three feet apart, but were offset in depth to avoid any interference. The two-stage impactor pitot was used to measure the gas velocity in the duct which was 21 m/sec. On the first test day the two-stage impactor with jet plate set I was run for two hours at a flow rate of 94 cm^3/sec and with jet plate set II for three hours at 47 cm^3/sec. Simultaneously an Andersen Stack Sampler was run at 236 cm^3/sec for five ours. On the second day the two-stage impactor with jet plate set III was run at 19 cm^3/sec for five hours and an Andersen Stack Sampler was also run for five hours at 236 cm^3/sec. On the first day the gas temperature was 166°C while on the second day it was 177°C. In all cases each impactor was allowed to warm up for 45 minutes before sampling was initiated. Appropriate nozzles were chosen to obtain as nearly isokinetic sampling as possible.

All sampling data are shown in Tables 4, 5, and 6. Figure 28 shows the two-stage impactor and Andersen impactor data presented on a cumulative mass basis. The discrepancies in total grain loading are not fully understood but may be partly due to sulfate absorption by the Andersen and two-stage impactor substrates. Sulfate determinations were run on all substrates used in these tests. Significant amounts of sulfate were found on the Andersen substrates and some was found on the two-stage impactor substrates as shown in Tables 4, 5, and 6. Results shown in Figure 28 are based on substrate weights gained corrected for sulfate weight gains. The flatness of the two-stage impactor curves may be due to either bounce or reentrainment of particles which passed to the filter.

On July 30-31, 1975 a second test of the two-stage impactor took place at Gorgas Steam Plant. Sampling was done on the outlet of Unit 10 again and all three jet plate sets were used. An Andersen Stack Sampler was run simultaneously with the two-stage

TABLE 4. TWO-STAGE IMPACTOR-JET PLATE SET 1

Nominal Flowrate 94 cm^3/sec June 25, 1975

Stage	Total Weight Gain (mg)	SO_4 (mg)	Corrected Weight Gain (mg)	Cumulative Loading (mg/ACM)
				TOTAL 8.28
1st	0.90	0.06	0.84	7.05
2nd	0.98	0.10	0.88	5.75
Back-up Filter	5.05	1.14	3.91	

Sampling Data

Calculated Flowrate	94.3 cm^3/sec
Ambient Pressure	29.5 "Hg
Gas Velocity	21.3 m/sec
Metering Orifice	0.059"
Metering Orifice ΔP	7.0" H_2O
Sampling System ΔP	8.0" H_2O
Metering Orifice Temperature	41°C
Impactor Temperature	166°C
Start Time	11:15 A.M.
End Time	1:15 P.M.
Duration	120 minutes
Nozzle	3.5 mm
Stack Pressure	-2.0 "H_2O
Flue Gas % H_2O by Volume	10%

Calculated 1st Stage D_{50} = 4.24 µm
Calculated 2nd Stage D_{50} = 1.14 µm

TABLE 5. TWO-STAGE IMPACTOR-JET PLATE SET II

Nominal Flowrate 47 cm^3/sec June 25, 1975

Stage	Total Weight Gain (mg)	SO_4 (mg)	Corrected Weight Gain (mg)	Cumulative Loading (mg/ACM)
				TOTAL 13.40
1st	1.66	0.07	1.59	10.28
2nd	2.46	0.10	2.36	5.65
Back-up Filter	4.86	1.98	2.88	

Sampling Data

Calculated Flowrate	45.1 cm^3/sec
Ambient Pressure	29.5 "Hg
Gas Velocity	21.1 m/sec
Metering Orifice	0.042"
Metering Orifice ΔP	4" H_2O
Sampling System ΔP	8" H_2O
Metering Orifice Temperature	41°C
Impactor Temperature	166°C
Start Time	2:30 P.M.
End Time	5:30 P.M.
Duration	180 minutes
Nozzle	1.5 mm
Stack Pressure	-2.0" H_2O
Flue Gas % H_2O by Volume	10%

Calculated 1st Stage D_{50} = 3.91 µm
Calculated 2nd Stage D_{50} = 0.82 µm

TABLE 6. TWO-STAGE IMPACTOR-JET PLATE SET III

Nominal Flowrate 19 cm^3/sec June 26, 1975

Stage	Total Weight Gain(mg)	SO_4 (mg)	Corrected Weight Gain(mg)	Cumulative Loading (mg/ACM)	
				TOTAL	12.65
1st	1.81	0.07	1.76		7.47
2nd	0.65	0.23	0.42		6.24
Filter	3.88	1.76	2.12		

SAMPLING DATA

Calculated Flowrate	20.0 cm^3/sec
Ambient Pressure	29.5" Hg
Gas Velocity	21.3 m/sec
Metering Orifice	0.029"
Metering Orifice ΔP	3" H_2O
Sampling System ΔP	6" H_2O
Metering Orifice Temperature	41°C
Impactor Temperature	177°C
Start Time	11:00 A.M.
End Time	4:00 P.M.
Duration	300 minutes
Nozzle	1 mm
Stack Pressure	-2" H_2O
Flue Gas % H_2O by Volume	10%

Calculated 1st Stage D_{50} = 1.81 µm
Calculated 2nd Stage D_{50} = 0.78 µm

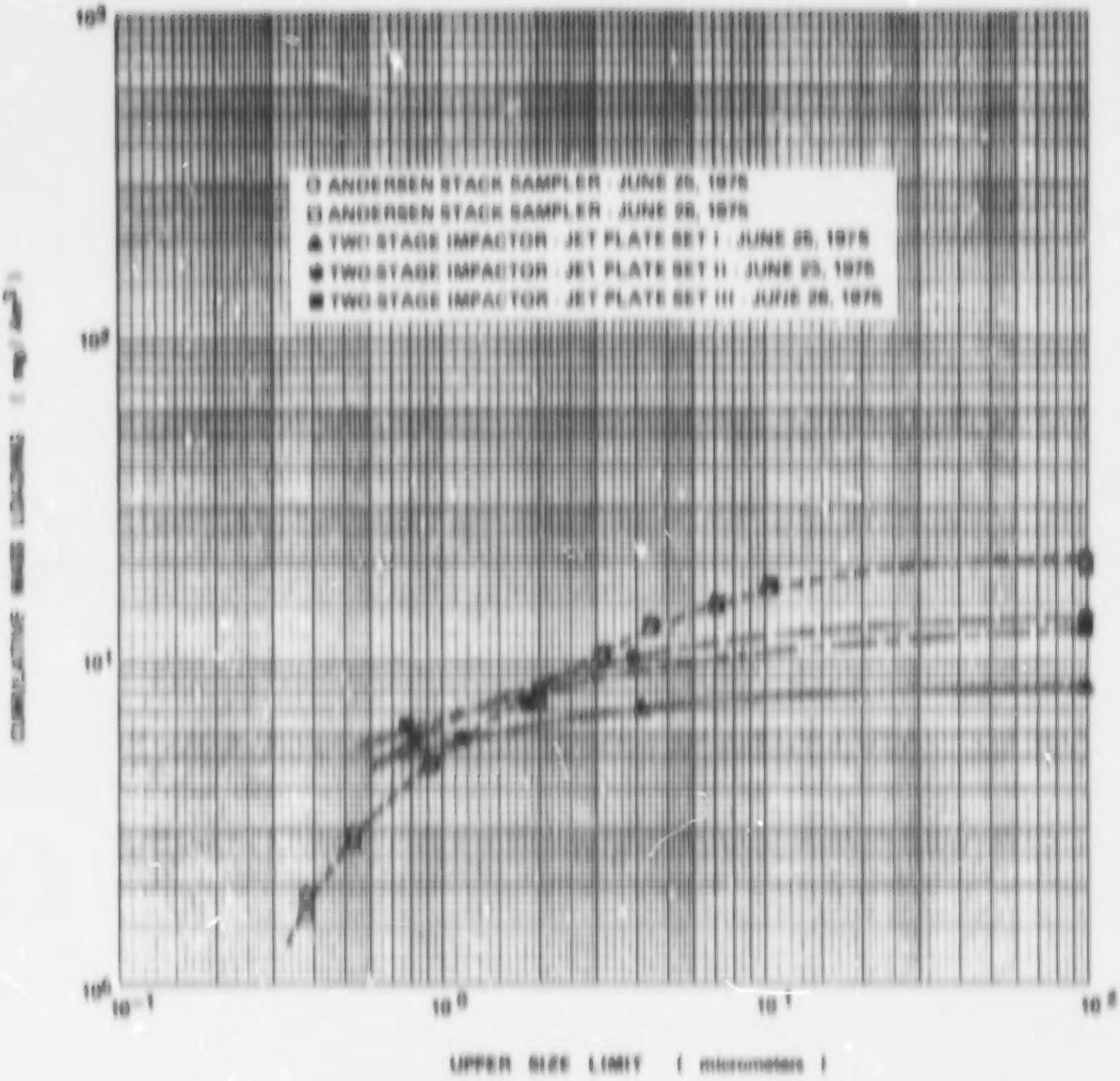

ANDERSEN STACK SAMPLER · JUNE 25, 1975
ANDERSEN STACK SAMPLER · JUNE 26, 1975
TWO STAGE IMPACTOR · JET PLATE SET I · JUNE 25, 1975
TWO STAGE IMPACTOR · JET PLATE SET II · JUNE 25, 1975
TWO STAGE IMPACTOR · JET PLATE SET III · JUNE 26, 1975
UPPER SIZE LIMIT (micrometers)

Figure 28. Cumulative grain loading versus Particle Size

impactor to obtain a comparable size distribution. In this series of tests, preconditioned substrates were used in both impactors to lessen the magnitude of the SO_2 interference. The substrates were conditioned by exposure to filtered flue gas for five hours before desiccation and initial weighing.

The two-stage impactor and Andersen were located at the same vertical level in the duct, three feet apart, but were offset in depth to avoid any interferences. The two-stage impactor pitot was used to measure the gas velocity which was 21.3 m/sec. On the first test day the two-stage impactor with jet plate set III was run at a flow rate of 19 cm^3/sec for five hours and an Andersen Stack Sampler was also run for five hours at 236 cm^3/sec. On the second day the two-stage impactor with jet plate set I was run for two hours at 94 cm^3/sec and with jet plate set II for three hours at 47 cm^3/sec. Simultaneously an Andersen Stack Sampler was again run at 236 cm^3/sec for five hours. On both days the flue gas temperature was 160°C. In all cases the impactors were allowed to warm up 45 minutes before sampling began. Appropriate nozzles were chosen to obtain as nearly isokinetic sampling as possible.

All two-stage impactor sampling data are shown in Tables 7, 8, and 9. Figure 29 shows the two-stage impactor and Andersen Stack Sampler data presented on a cumulative mass basis.

Reasonable agreement can be seen between the two-stage impactor and Andersen impactor data. This is in contrast to the poor agreement between the two impactor data presented for the June 25-26 test. The preconditioning of the substrates has aided in this agreement and it appears that reliable information with this two-stage impactor is attainable when care is taken in all aspects of the sampling, including preconditioning the collection substrates.

TABLE 7. TWO-STAGE IMPACTOR -- JET PLATE SET 1

Nominal Flowrate -- 94 cm^3/sec July 11, 1975

Stage	Weight Gain(mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50}(um)
		TOTAL 5.83	
1st	0.42	5.34	3.69
2nd	2.46	3.50	0.99
Back-up Filter	2.17		

SAMPLING DATA

Calculated Flowrate	120.36 cm^3/sec
Ambient Pressure	29.3" Hg
Gas Velocity	21.1 m/sec
Metering Orifice	0.059"
Metering Orifice ΔP	7.94" H_2O
Sampling System ΔP	19" H_2O
Metering Orifice Temperature	21°C
Impactor Temperature	160°C
Start Time	2:20 p.m.
End Time	4:20 p.m.
Duration	120 minutes
Nozzle	2.5 mm
Stack Pressure	-1.6" H_2O
Flue Gas % H_2O by Volume	10%

TABLE 8. TWO-STAGE IMPACTOR -- JET PLATE SET II

Nominal Flowrate -- 47 cm³/sec July 31, 1975

Stage	Weight Gain(mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50}(um)
	TOTAL	9.57	
1st	0.45	8.60	3.91
2nd	1.51	5.42	0.82
Back-up Filter	2.59		

SAMPLING DATA

Calculated Flowrate	44.23 cm³/sec
Ambient Pressure	29.3" Hg
Gas Velocity	21.3 m/sec
Metering Orifice	0.042"
Metering Orifice ΔP	4.2" H_2O
Sampling System ΔP	8.0" H_2O
Metering Orifice Temperature	21°C
Impactor Temperature	160°C
Start Time	10:10 a.m.
End Time	1:10 p.m.
Duration	180 minutes
Nozzle	1.5 mm
Stack Pressure	-1.8" H_2O
Flue Gas % H_2O by Volume	10%

TABLE 9. TWO-STAGE IMPACTOR -- JET PLATE SET III

Nominal Flowrate -- 19 cm³/sec July 30, 1975

Stage	Weight Gain (mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50} (mg)
	TOTAL	8.48	
1st	0.93	5.99	1.75
2nd	0.83	5.77	0.75
Back-up Filter	1.41		

SAMPLING DATA

Calculated Flowrate	20.77 cm³/sec
Ambient Pressure	29.3" Hg
Gas Velocity	21.3 m/sec
Metering Orifice	0.029"
Metering Orifice ΔP	3.73" H_2O
Metering Orifice Temperature	27°C
Sampling System ΔP	6" H_2O
Impactor Temperature	160°C
Start Time	11:35 a.m.
End Time	4:35 p.m.
Duration	300 minutes
Nozzle	1.0 mm
Stack Pressure	-1.8" H_2O
Flue Gas % H_2O by Volume	10%

Figure 20. Cumulative Grain Loading versus Particle Size
Particle Diameter, um

Oil-Fired Power Plant--

On January 28-29, 1976 tests of the two-stage impactor were made at an oil-fired power plant. No pollution control device was installed at this facility. Two adjacent ports were used for sampling. Each of the three sets of jet plates were run at least once during the testing period. Glass fiber collection substrates were used in all impactor tests. An Andersen Stack Sampler was run at approximately the same time intervals to obtain a comparable size distribution. The collection substrates for both the two-stage and the Andersen impactors were preconditioned instack by exposure to filtered flue gas. Blank runs for the Andersen were made and collection weights accordingly adjusted for SO_x weight gains.

Ultrafine particle measurements were also done as part of these tests. These measurements were made with Thermo-Systems' Electrical Aerosol Size Analyzer (EAA). A dilution system developed at SRI was used to lower the particle concentration to a level suitable for the EAA. This device is used to obtain a particle size distribution over the 0.013 to 0.31 micrometer range, which is just below that of the inertial impactor.

The power plant was operated at three load conditions during the testing period: full load, half load, and maximum load. The first day of the test was at full load, the morning of the second day was at maximum load and the afternoon of the second day was at half load.

Two measurements were made with the Andersen Stack Sampler at the full load condition. The PSC impactor was used with plate sets I and II at the full load condition. Two Andersen tests were also made at the half load condition, and only plate set III of the PSC impactor was used at this load. For the maximum load condition, only the PSC impactor with plate set I was run and because of a miscalculation, an anisokinetic sample was taken. Large particles were probably over sampled during this test. The results of this test are plotted on the graphs for the full load condition. Again, the impactors were allowed at least 45 minutes warm-up time before sampling was begun.

All sampling data for the PSC impactor runs, including flowrates, stack temperatures, and sampling time, are shown in Tables 10, 11, 12, and 13. Figures 30 and 31 show the cumulative particle size distributions for the full and half load conditions. Figures 32 and 33 show the differential particle size distribution on a mass basis and Figures 34 and 35 show the differential size distributions on a numerical basis. Figure 36 is a cumulative

TABLE 10. TWO-STAGE IMPACTOR -- JET PLATE SET 1

Nominal Flowrate 94 cm³/sec January 28, 1976

Stage	Weight Gain (mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50} (μm)
		TOTAL: 139.84	
1st	10.66	42.22	6.39
2nd	0.82	14.71	1.77
Back-up Filter	1.79		

Sampling Data

Calculated Flowrate	91.0 cm³/sec
Ambient Pressure	30.2" Hg
Gas Velocity	18.1 m/sec
Metering Orifice	0.059"
Metering Orifice ΔP	5" H_2O
Sampling System ΔP	1.25" Hg
Metering Orifice Temperature	21°C
Impactor Temperature	138°C
Start Time	11:10 a.m.
End Time	11:30 a.m.
Duration	20 min.
Nozzle	2.5 mm
Stack Pressure	+3.0 "H_2O
Flue Gas % H_2O by Volume	10.5%

TABLE 11. TWO-STAGE IMPACTOR -- JET PLATE SET II

Nominal Flowrate 47 cm³/sec January 16, 1976

Stage	Weight Gain (mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50} (μm)
		TOTAL: 48.47	
1st	4.75	20.60	5.19
2nd	0.61	16.90	1.12
Back-up Filter	2.88		

Sampling Data

Calculated Flowrate	56.8 cm³/sec
Ambient Pressure	30.2" Hg
Gas Velocity	18.3 m/sec
Metering Orifice	0.042"
Metering Orifice ΔP	6.3" H_2O
Sampling System ΔP	0.17" Hg
Metering Orifice Temperature	21°C
Impactor Temperature	147°C
Start Time	3:25 p.m.
End Time	4:15 p.m.
Duration	50 min.
Nozzle	2 mm
Stack Pressure	+ 3.0" H O
Flue Gas % H_2O by Volume	10.5%

TABLE 12. TWO-STAGE IMPACTOR -- JET PLATE SET 1

Nominal Flowrate 94 cm^3/sec January 29, 1976

Stage	Weight Gain (mg)	Cumulative Loading (mg/ACM)	Calculated Stage D$_{50}$ (um)
		TOTAL: 106.08	
1st	4.51	14.35	8.52
2nd	0.61	24.65	2.39
Back-up Filter	1.55		

Sampling Data

Calculated Flowrate	52.4 cm^3/sec
Ambient Pressure	30.1" Hg
Gas Velocity	18.3 m/sec
Metering Orifice	0.042"
Metering Orifice ΔP	5" H_2O
Sampling System ΔP	0.22" Hg
Metering Orifice Temperature	7.2°C
Impactor Temperature	149°C
Start Time	9:29 a.m.
End Time	9:49 a.m.
Duration	20 min.
Nozzle	2.5 mm
Stack Pressure	+3.0" H_2O
Flue Gas % H_2O by Volume	10.5%

TABLE 13. TWO-STAGE IMPACTOR -- JET PLATE SET III

Nominal Flowrate 19 cm^3/sec January 29, 1976

Stage	Weight Gain (mg)	Cumulative Loading (mg/ACM)	Calculated Stage D_{50} (um)
		TOTAL: 45.94	
1st	2.47	26.10	3.48
2nd	0.22	24.34	1.55
Back-up Filter	3.03		

Sampling Data

Calculated Flowrate	12.5 cm^3/sec
Ambient Pressure	30.1" Hg
Gas Velocity	6.5 m/sec
Metering Orifice	0.029"
Metering Orifice ΔP	1.2" H_2O
Sampling System ΔP	0.15" Hg
Metering Orifice Temperature	20°C
Impactor Temperature	143°C
Start Time	12:06 p.m.
End Time	2:52 p.m.
Duration	166 min.
Nozzle	1 mm
Stack Pressure	0
Flue Gas % H_2O by Volume	10.5%

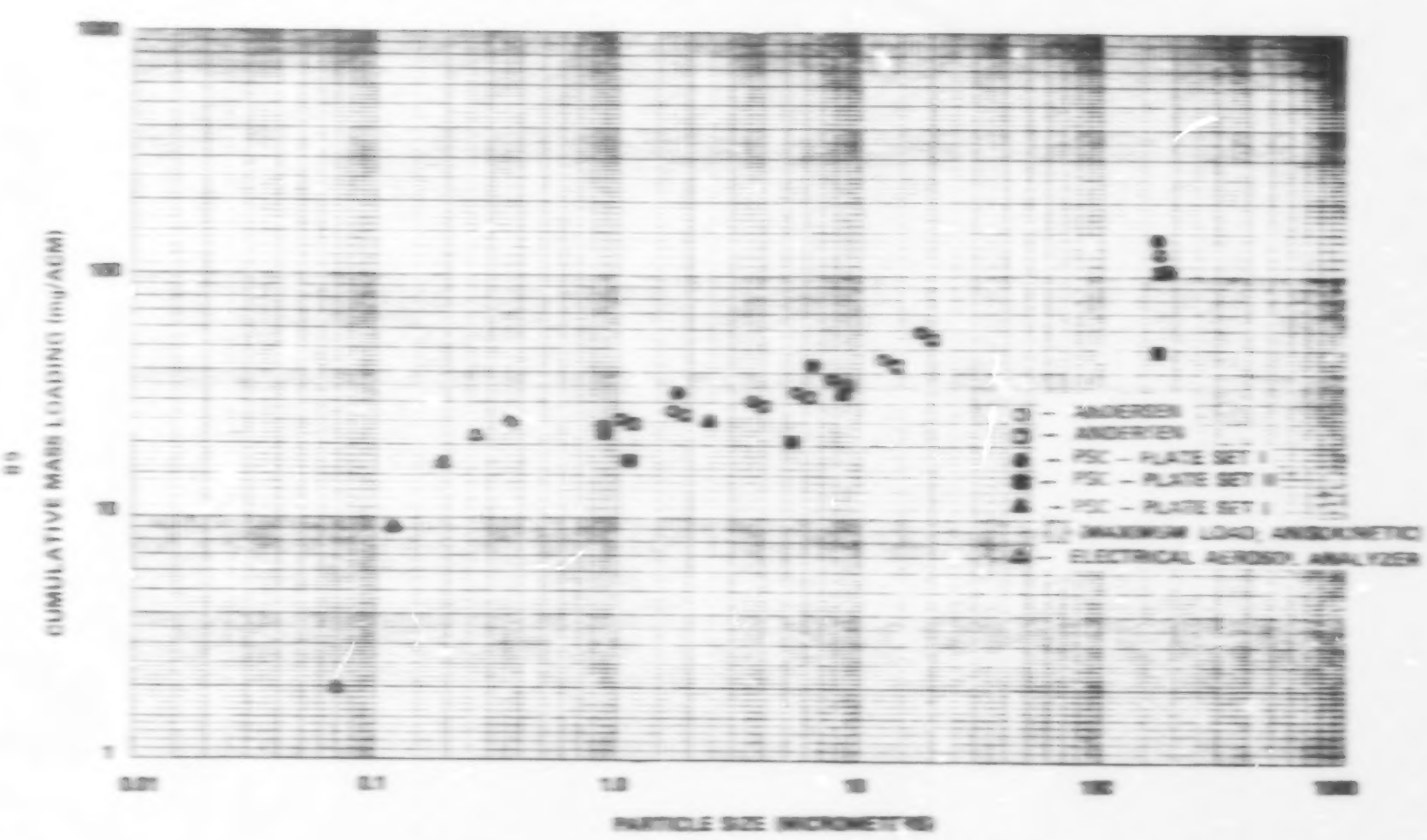


Figure 38. Cumulative Particle Size Distribution for Full Load

January 28, 1976

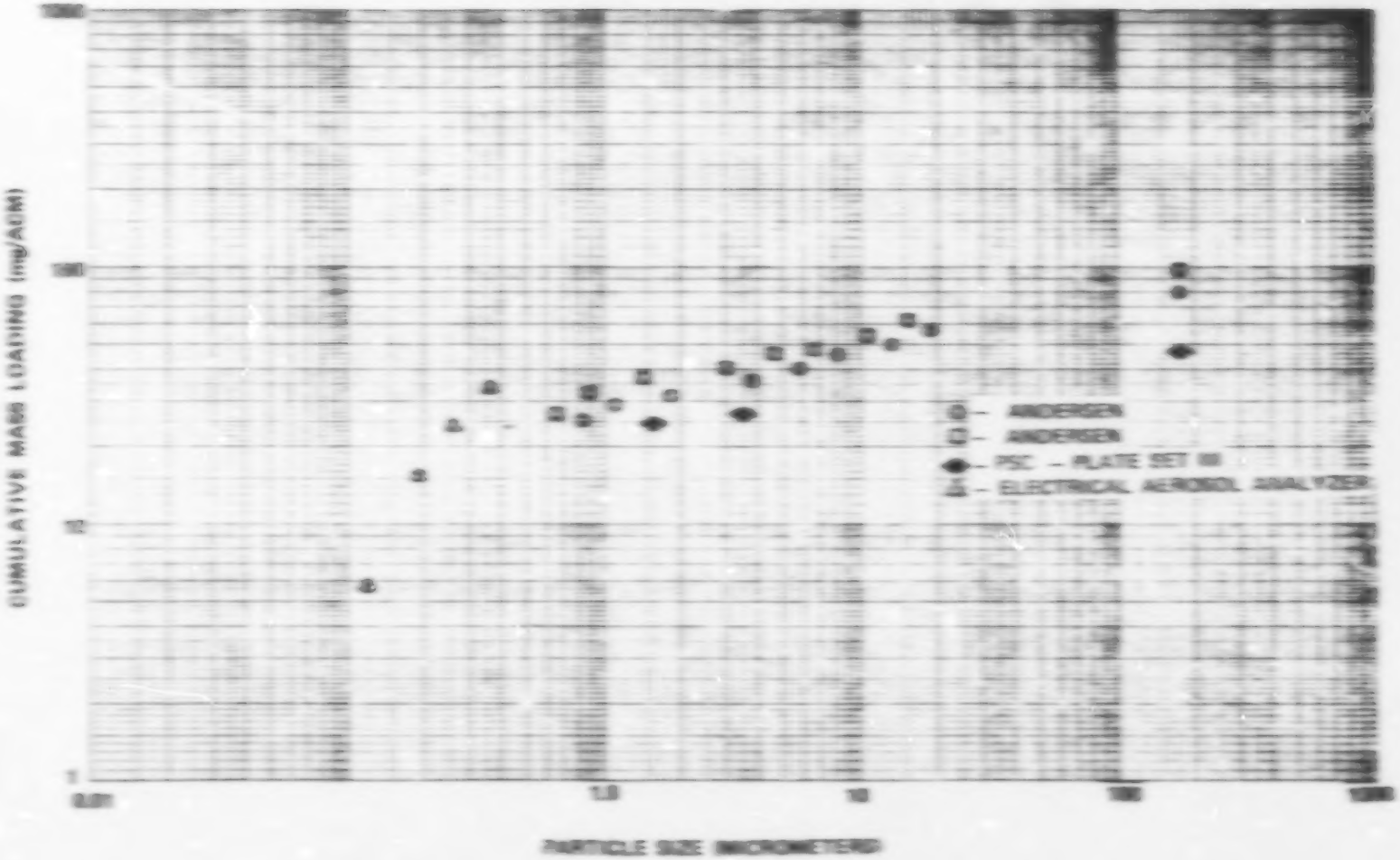


Figure II. Cumulative Particle Size Distribution for Salt Lead, January 29, 1976

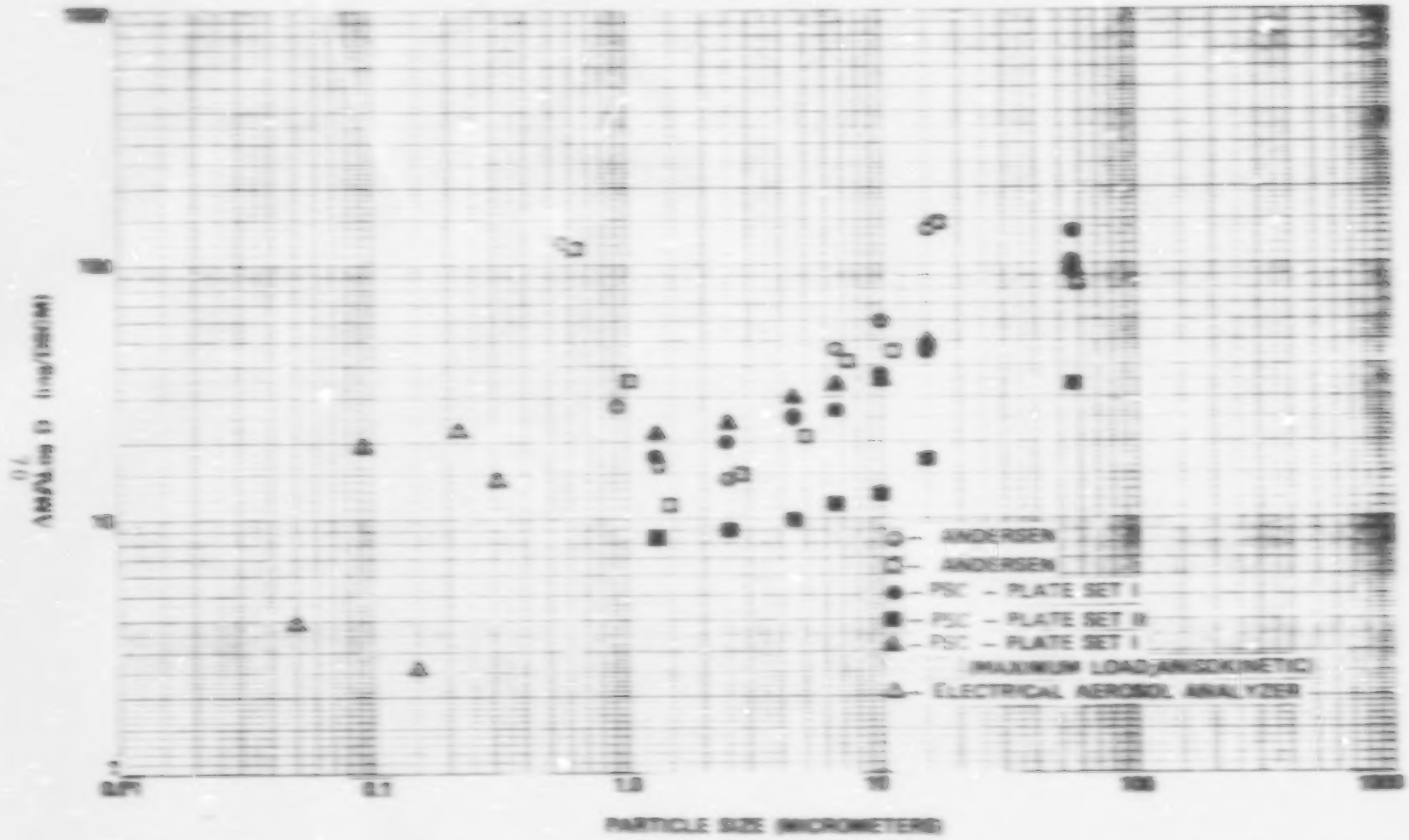


Figure 37. Differential Particle Size Distribution on Mass Basis for Full Load, January 28, 1976

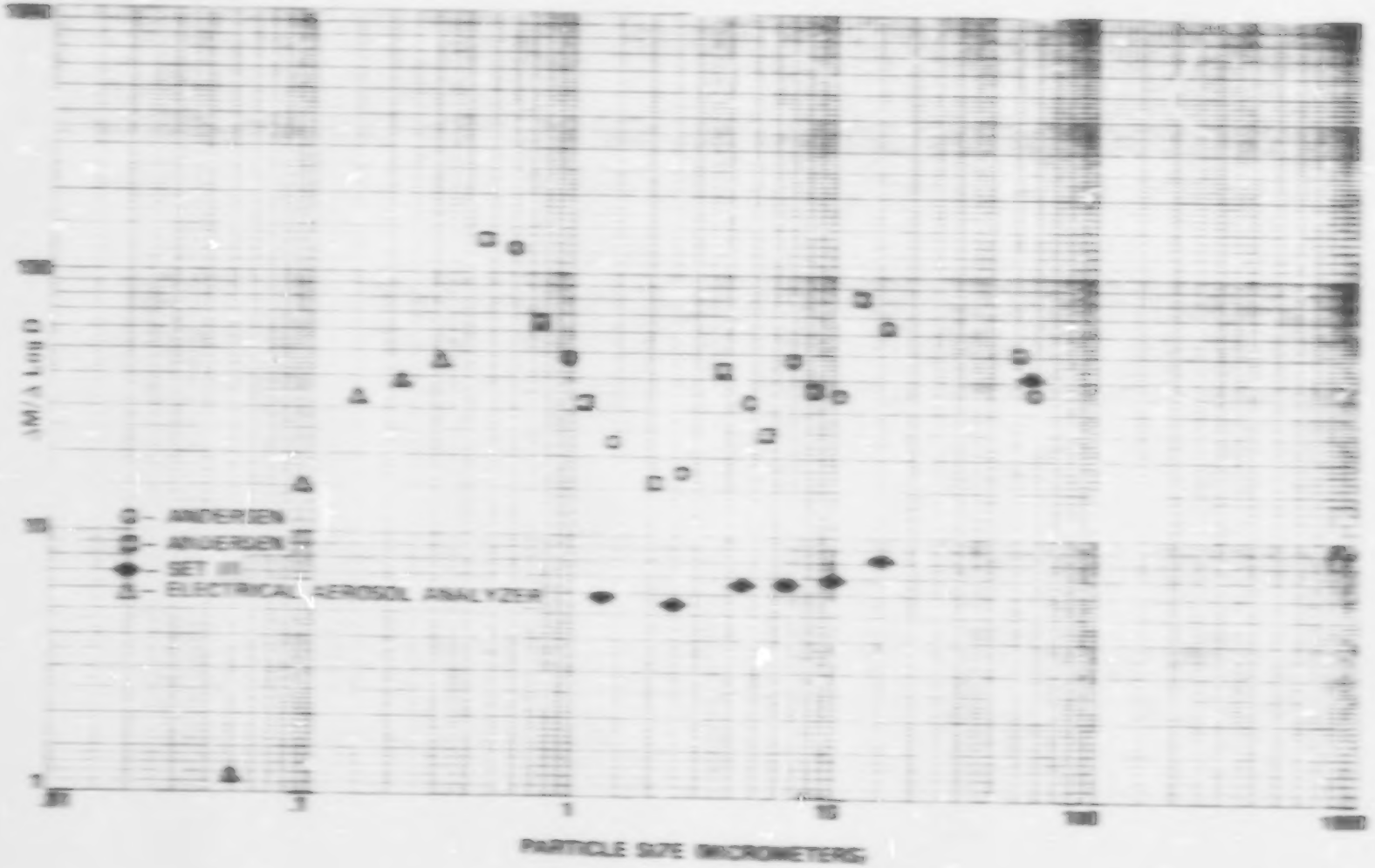


Figure 33. Differential Particle Size Distribution on Mass Basis for Half Load, January 29, 1976

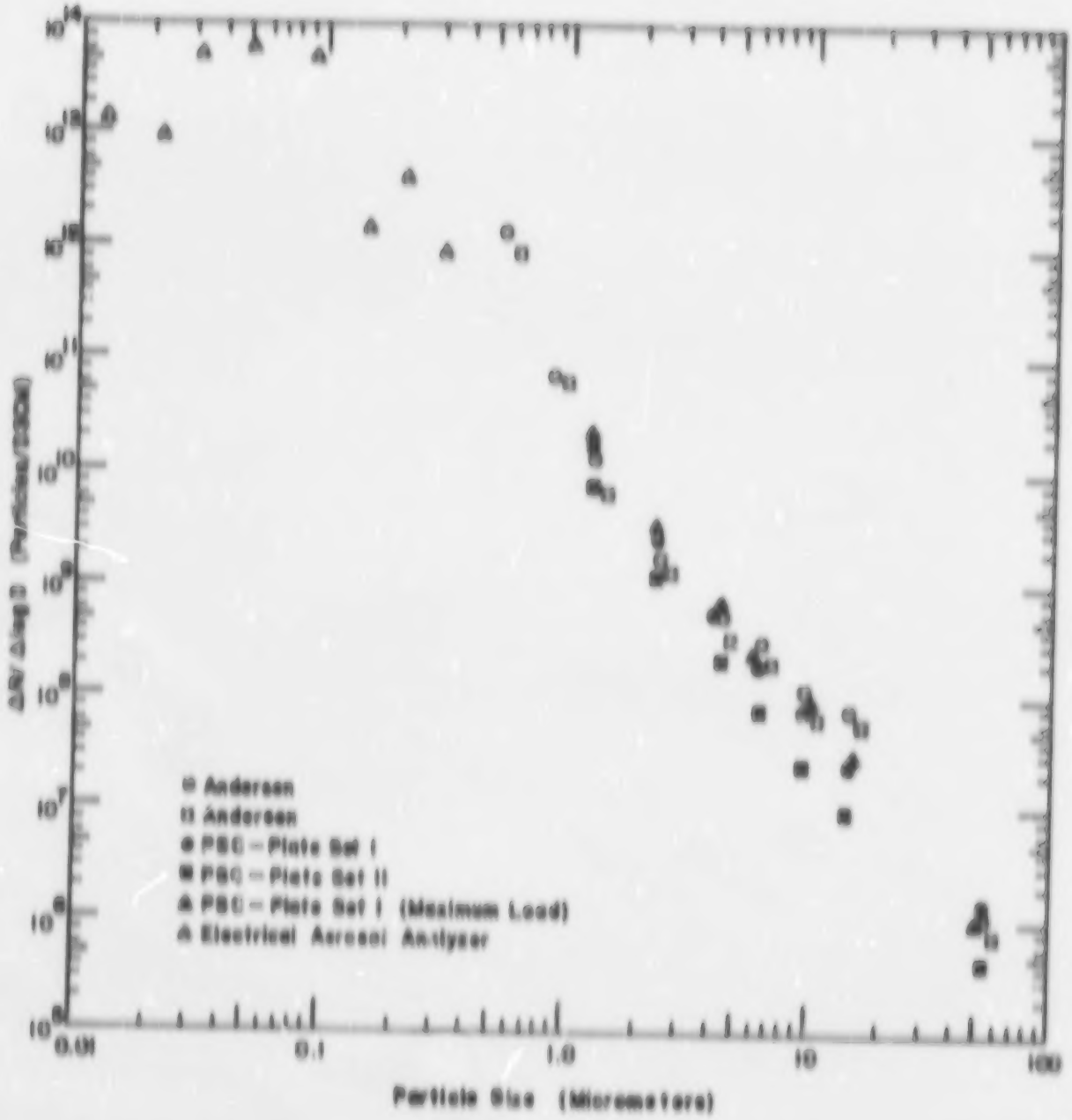


Figure 14. Differential Particle Size Distribution on Numerical Basis for Full Load, January 28, 1976

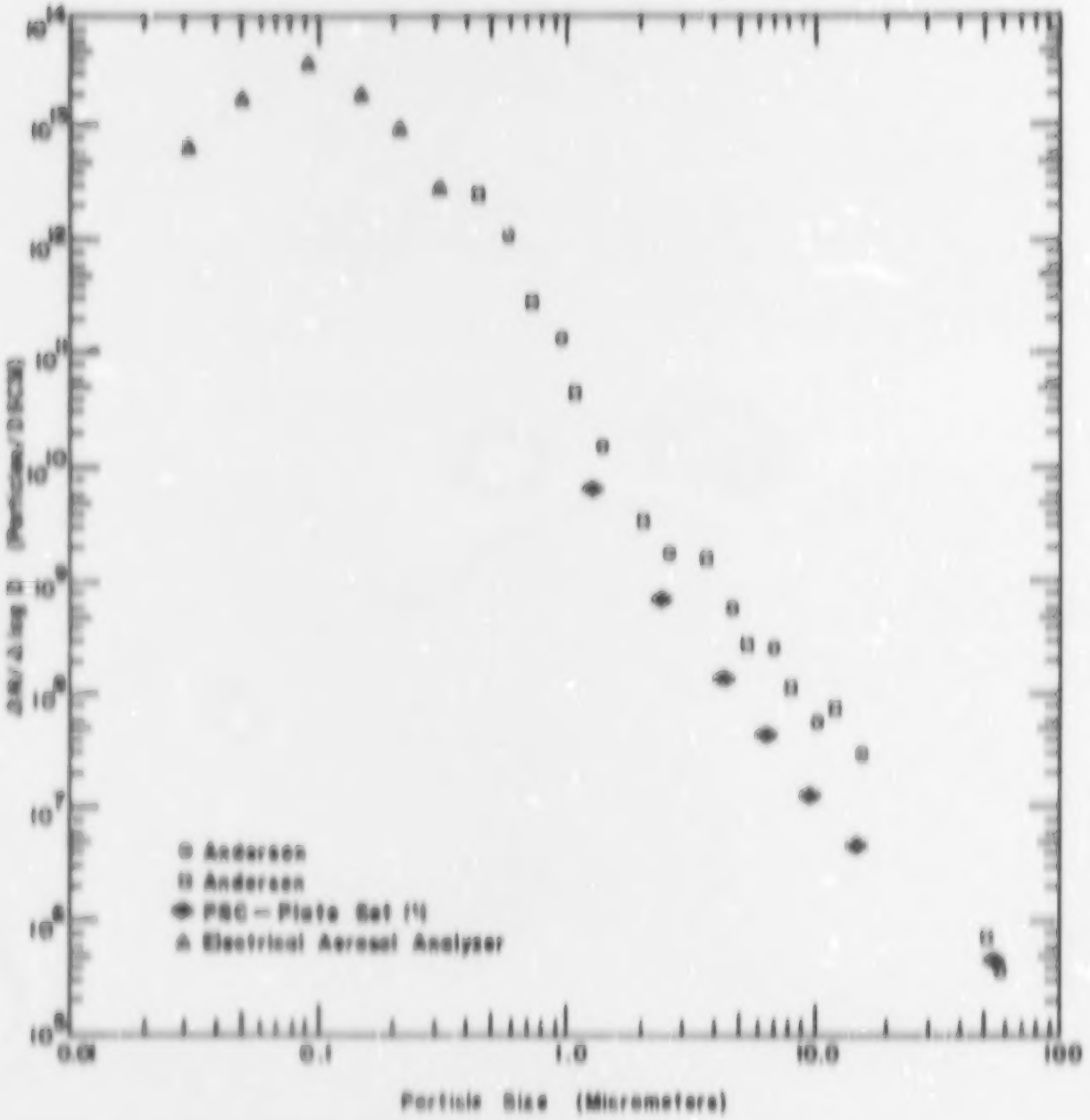


Figure 35. Differential Particle Size Distribution on Numerical Basis for Half Load, January 29, 1976

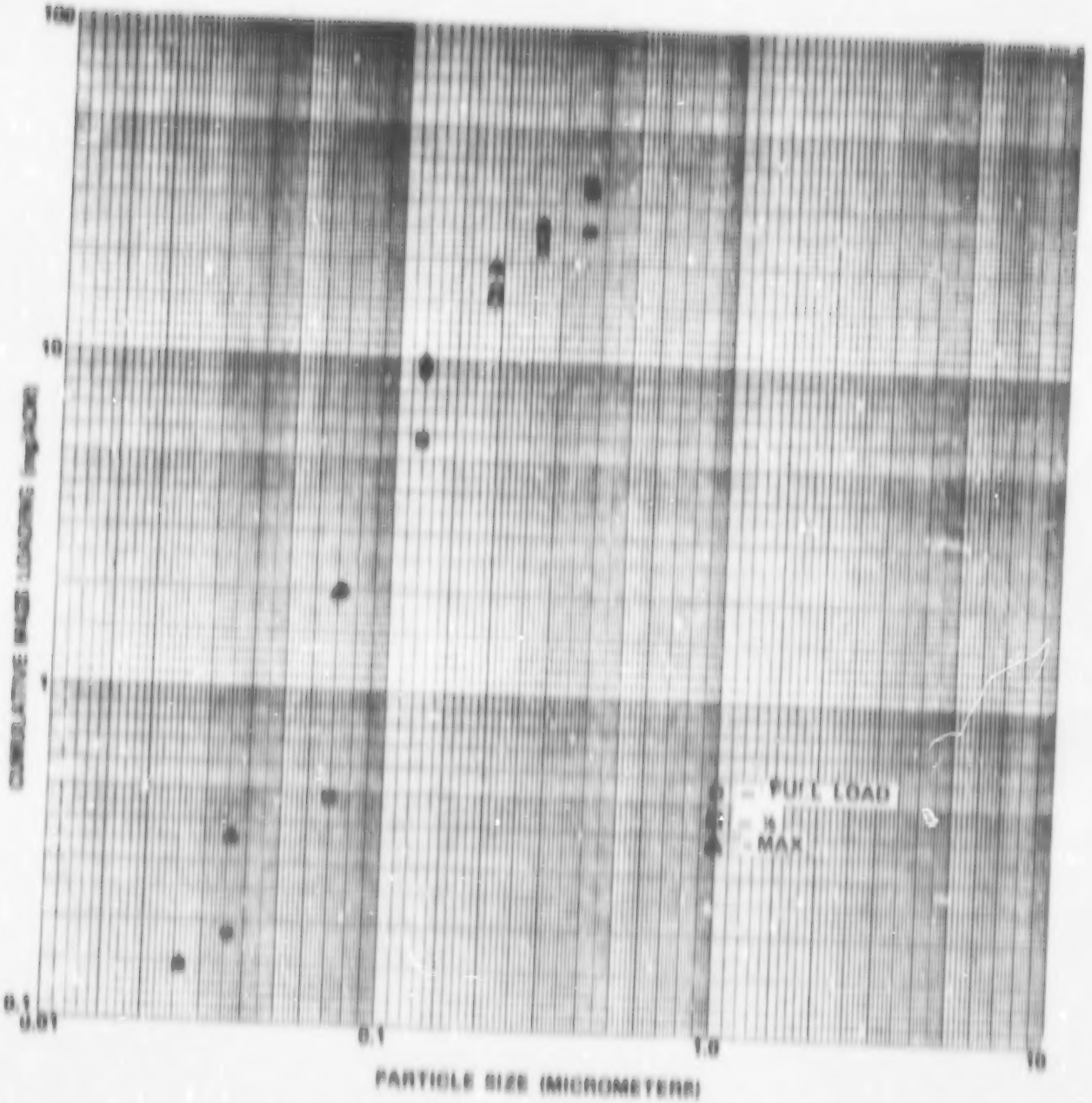


Figure 16. Cumulative Particle Size Distribution for Ultrafine Region Using the Electrical Aerosol Analyser, January 28-29, 1976

size distribution of the ultrafine particles for all three load conditions as seen by the Electrical Aerosol Analyser. There was no detectable changes in the ultra-fine particle size distribution with the plant load condition.

The differential size distributions for the PSC impactor were derived from the cumulative distributions. For accurate comparison with the Andersen runs, intervals from the PSC cumulative curves were chosen such that they were approximately the same as those on the Andersen curves. The PSC differential curves were then determined from these cumulative loadings.

There is reasonable data agreement between the Andersen Stack Sampler and the PSC impactor. Data from both impactors were in good alignment with the EAA ultrafine data.

From the results of this field test and the previous two tests, it is seen that good agreement of the PSC impactor with commercial instruments can be obtained. The only restrictions are those that apply to the commercial instruments also--that the impactor is carefully used as it was designed to be. This means that isokinetic sampling is a must; the correct nozzle must be used; the flow rate must be accurate and constant; and all other basic rules of stack sampling must be adhered to. Only when these rules are closely and carefully followed, can good, reliable, particle-size data be obtained.

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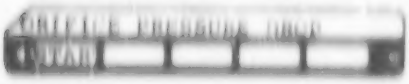
APPENDIX

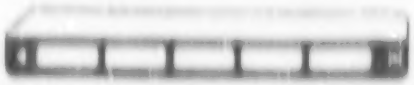
CALCULATOR PROGRAMS FOR THE FSC IMPACTORS

HP-65 User Instructions

Title: Sampling Orifice Pressure Drop Calculations - Two-Stage Impactor

Prog name:





STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Input desired sampling flowrate.	(cm^3/sec)			
2	Store desired sampling flowrate.		STO	1	
3	Input calibration flowrate at 10" H_2O.	(cm^3/sec)			
4	Store calibration flowrate.		STO	2	
5	Input flue gas volume fraction of water.				
6	Store flue gas volume fraction of water.		STO	3	
7	Input ambient pressure at impactor inlet.	("Hg)			
8	Store ambient pressure at impactor inlet.		STO	4	
9	Input orifice calibration ambient pressure.	("Hg)			
10	Store orifice calibration ambient pressure.		STO	5	
11	Input orifice temperature when sampling.	(^oC)			
12	Store orifice temperature when sampling.		STO	6	
13	Input impactor gas exit temperature.	(^oC)			
14	Store impactor gas exit temperature.		STO	7	
15	Input orifice temperature when calibrated.	(^oC)			
16	Store orifice temperature when calibrated.		STO	8	
17	Begin calculation.		A		
18	Read orifice pressure drop.				("H_2O)

HP-65 Program Form

Title: Sampling Orifice Pressure Drop Calculation--Two-Stage Impactor

KEY ENTRY	CODE SHOWN	COMMENTS
LBL	21	
A	11	
1	01	
0	00	
Enter↑	41	
RCL 1	16 01	
×	71	
RCL 1	16 01	
×	71	
RCL 2	16 02	
÷	81	
RCL 2	16 02	
÷	81	
FCL 1	16 01	
CHS	42	
1	01	
+	61	
3	03	
×	71	
RCL 3	16 03	
CHS	42	
1	01	
+	61	
3	03	
×	71	
RCL 4	16 04	
×	71	
RCL 5	16 05	
÷	81	
RCL 6	16 06	
2	02	
7	07	
3	03	
+	61	
×	71	
RCL 8	16 08	
2	02	
7	07	
3	03	
+	61	
×	71	
RCL 7	16 07	
2	02	
7	07	
3	03	
+	61	
÷	81	
RCL 7	16 07	
2	02	
7	07	
3	03	
+	61	

KEY ENTRY	CODE SHOWN	COMMENTS
÷	81	
RTN	24	

REGISTER

R₀ Sampling Flowrate (cm³/sec)
R₁ Orifice Flowrate (cm³/sec)
R₂ Fraction of H₂O
R₃ Pressure At Inlet ("Hg)
R₄ Calibration Pressure ("Hg)
R₅ Orifice Temp. (°C)
R₆ Impactor Temp. (°C)
R₇ Calibration Temp. (°C)
R₈
R₉

LABELS
A Start
B
C
D
E
0
1
2
3
4
5
6
7
8
9

FLAGS
1
2

HP-65 User Instructions

Title: Particle Size Distribution Calculations--Two-Stage Impactor

Program: [illegible]

STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Input 1st Stage collected mass.	(mg)			
2	Store 1st stage collected mass.		STO	1	
3	Input 2nd stage collected mass.	(mg)			
4	Store 2nd stage collected mass.		STO	2	
5	Input filter collected mass.	(mg)			
6	Store filter collected mass.		STO	3	
7	Input sampling flowrate.	(cm^3/sec)			
8	Store sampling flowrate.		STO	4	
9	Input sampling duration.	(min)			
10	Store sampling duration.		STO	5	
11	Input impactor gas stream temperature.	(^oC)			
12	Store impactor gas stream temperature.		STO	6	
13	Input impactor inlet ambient pressure.	("Hg)			
14	Store impactor inlet ambient pressure.		STO	7	
15	Input flue gas volume fraction of water.				
16	Store flue gas volume fraction of water.		STO	8	
17	Begin calculation.		A		
18	Cumulative mass loading to 2nd stage cut point.		RCL	1	(mg/ACM)
19	Cumulative mass loading to 1st stage cut point.		RCL	2	(mg/ACM)
20	Cumulative mass loading to 2nd stage cut point.		RCL	3	(mg/DNCM)
21	Cumulative mass loading to 1st stage cut point.		RCL	4	(mg/DNCM)
22	Total mass loading.		RCL	5	(mg/ACM)
23	Total mass loading.		RCL	6	(mg/DNCM)
24	Cumulative percent to 2nd stage cut point.		RCL	7	(%)
25	Cumulative percent to 1st stage cut point.		RCL	8	(%)

HP-65 Program Form

Title: Particle Size Distribution Calculation--Two-Stage Impactor

KEY ENTRY	CODE SHOWN	COMMENTS
LBL	21	
A	11	
RCL 1	34 01	
RCL 2	34 02	
+	61	
RCL 3	34 03	
+	61	
RCL 4	34 04	
+	61	
RCL 5	34 05	
+	61	
6	06	
0	00	
+	61	
1	01	
GSB	43	
6	06	
X	71	
STO 4	33 04	
RCL 6	34 06	
2	02	
7	07	
3	03	
+	61	
RCL 4	34 04	
X	71	
2	02	
6	06	
-	81	
9	09	
2	02	
1	01	
X	71	
2	02	
9	09	
5	05	
+	61	
RCL 7	34 07	
+	61	
RCL 8	34 08	
CHS	42	
1	01	
+	61	
+	61	
STO 5	33 05	
RCL 1	34 01	
RCL 2	34 02	
+	61	
RCL 3	34 03	
+	61	

KEY ENTRY	CODE SHOWN	COMMENTS
STO 6	33 06	
RCL 1	34 01	
RCL 6	34 06	
-	81	
STO 7	33 07	
RCL 1	34 01	
RCL 2	34 02	
+	61	
RCL 6	34 06	
-	81	
STO 8	33 08	
RCL 5	34 05	
STO 6	33 06	
RCL 4	34 04	
STO 5	33 05	
RCL 7	34 07	
RCL 5	34 05	
X	71	
STO 1	33 01	
RCL 8	34 08	
RCL 5	34 05	
X	71	
STO 2	33 02	
RCL 7	34 07	
RCL 6	34 06	
X	71	
STO 3	33 03	
RCL 8	34 08	
RCL 6	34 06	
X	71	
STO 4	33 04	
RCL 7	34 07	
1	01	
0	00	
0	00	
X	71	
STO 7	33 07	
RCL 8	34 08	
1	01	
0	00	
0	00	
X	71	
STO 8	33 08	
RTN	24	

REGISTER

R1 1st Stage Weight (mg)

R2 2nd Stage Weight (mg)

R3 Filter Weight (mg)

R4 Flowrate (cm^3/sec)

R5 Duration (min.)

R6 Temp. (°C)

R7 Pressure ("Hg)

R8 Fraction of H_2O

R9

LABELS

A Start
B
C
D
E
0
1
2
3
4
5
6
7
8
9

FLAGS

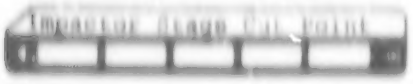
1

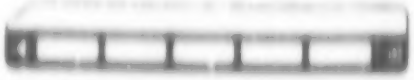
2

HP-65 User Instructions

Title: Impactor Stage Cut Point Calculations Two-Stage Impactor

Prog. Name:





STEP	INSTRUCTIONS	INPUT DATA/UNITS	KEYS		OUTPUT DATA/UNITS
1	Input flue gas viscosity.	(poise)			
2	Store flue gas viscosity.		STO	1	
3	Input ambient pressure at impactor inlet.	("Hg)			
4	Store ambient pressure at impactor inlet.		STO	2	
5	Input impactor exit gas temperature.	(^{o}C)			
6	Store impactor exit gas temperature.		STO	3	
7	Input diameter of stage jets.	(cm)			
8	Store diameter of stage jets.		STO	4	
9	Input number of jets.				
10	Store number of jets.		STO	5	
11	Input particle density of particulate.	(gm/cm^{3})			
12	Store particle density of particulate.		STO	6	
13	Input impactor sampling flowrate.	(cm^{3}/sec)			
14	Store impactor sampling flowrate.		STO	7	
15	Input jet plate constant. (See other sheet.)				
16	Store jet plate constant.		STO	8	
17	Begin calculation.		A		(micro-material)
18	Observe resulting stage cut point.				(micro-material)

HP-65 Program Form

Title: Impactor Stage Cut Point Calculations-- Two-Stage Impactor

KEY ENTRY	CODE SHOWN	COMMENTS
LBL	21	
A	A	
RCL 3	34 03	
.	83	
0	00	
0	00	
3	03	
6	06	
7	07	
x	71	
1	01	
.	83	
3	03	
0	00	
.	83	
0	00	
2	02	
1	01	
x	71	
STO 0	33 00	
RCL 1	34 01	
x	71	
RCL 2	34 02	
x	71	
RCL 0	34 00	
Enter	41	
3	03	
0	00	
y^x	05	
RCL 5	34 05	
x	71	
RCL 1	34 01	
x	71	
RCL 0	34 00	
x	71	
RCL 7	34 07	
.	83	
RCL 6	34 06	
.	83	
Enter	41	
3	03	
2	02	

KEY ENTRY	CODE SHOWN	COMMENTS
3	03	
0	00	
.	83	
0	00	
Enter	41	
RCL 1	34 01	
x	71	
RCL 1	34 01	
x	71	
RCL 2	34 02	
.	83	
RCL 9	34 09	
.	83	
1	01	
y^x	31	
√x	09	
Enter	41	
RCL 3	34 03	
Enter	41	
RCL 3	34 03	
x	71	
y^x	31	
√x	09	
0	35	
1/x	04	
RCL 1	34 01	
x	71	
0	00	
3	03	
.	83	
0	00	
CHS	42	
x	71	
1	01	
RTN	24	

(*) Jet Plate Constant
Based on Calibration Results

10 µm at 0.2 cfm	5.10 E8X7
2 µm at 0.2 cfm	1.07 E8X8
0 µm at 0.1 cfm	1.56 E8X8
1 µm at 0.1 cfm	1.94 E8X8
2 µm at 0.04 cfm	1.07 E8X8
1 µm at 0.04 cfm	1.78 E8X8

REGISTERS

R1 Viscosity (Poise)

R2 Pressure ("Hg)

R3 Temp. (°C)

R4 Jet Dia (cm)

R5 No. of Jets

R6 Density (gm/cm³)

R7 Flowrate (cm³/sec)

R8 Constant (*)

R9

LABELS

A Start
B
C
D
E
0
1
2
3
4
5
6
7
8
9

FLAGS

1
0

END